CONTROLS ON LANDCOVER PATTERNS IN TWO ADJACENT STREAM CATCHMENTS, SOUTH-EAST SPAIN

Thesis submitted in accordance with the requirements of the University of Liverpool for the degree of Doctor in Philosophy by Katherine Joan Willshaw

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ABSTRACT

The Sorbas basin lies within the Betic Cordillera of south-east Spain. It is a recently uplifted sedimentary basin with readjustment of drainage systems still occurring, and hence intense erosion is found in places. This erosion, coupled with a semi-arid climate and a history of human impact has lead to a variably patchy vegetation cover throughout the catchment. This thesis examines controls on vegetation cover patchiness in a pair of adjacent catchments using a landscape ecology approach. These catchments display contrasting patterns of landcover and represent two stages in an erosion-stabilisation cycle driven by base level change on the Rio Aguas into which they both drain.

Cover and species type data were collected in the field along with soil samples. The vegetation analysis programs DECORANA and TWINSPAN were used to explore the cover and species data collected in the field. Results of the analyses were correlated with environmental variables to identify controls on distribution. Airborne Thematic Mapper (ATM) data were acquired from a NERC ARSF flight in 1996 along with aerial photographs of the study area. The ATM data were used to produce a clustered landcover image based upon the clustering of an NDVI image followed by interpretation of the six end groups using the cover data collected in the field. The aerial photography was used to produce a digital elevation model, and from this the environmental variables aspect, slope gradient and wetness were derived. The digital elevation model was also used in conjunction with the aerial photographs to produce an orthorectified image of the study area.

Geology was found to be the most significant control on cover type distribution, closely followed by geomorphology and soil chemistry. Species type distribution is also strongly controlled by geology with geomorphological history being almost as significant, and soil chemistry controlling the distribution at a fine scale. Slope gradient and aspect were not particularly associated with either cover or species distribution. The clustered landcover image, in which the six classes of cover ranged from very sparse to very densely vegetated, was analysed in conjunction with aspect, slope gradient and wetness to identify which of variable had the closest relationship with cover distribution. It was found that aspect had greatest association with cover, and wetness the least. However, all three show a statistically significantly relationship to cover class. The clustered landcover image was then used in conjunction with FRAGSTATS, a landscape metrics program, and a class buffering technique was used in order to quantify the landcover patterns in the two catchments. The quantification of pattern enabled an assessment of the relative controls of each of the environmental variables on the cover pattern in both catchments. Geology was found to be the most important control on the cover distribution, with geomorphological history and aspect important at a finer scale. Slope gradient, wetness and soil chemistry were not found to be very significant controlling factors.

Acknowledgements

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PLATES

FIGURES

TABLES

GLOSSARY OF IMPORTANT TERMS

ATM	airborne thematic mapper. A multi-band sensor used to collect remotely sensed imagery
Classification (image)	the process of assigning the pixels of a multi-band raster image to discrete categories
Classification (plants)	the process of grouping together a set of vegetation samples on the basis of their attributes
Clustering (image)	the process of assigning pixels of a one band rater image to discrete categories
DECORANA	Detrended CORrespondence ANAlysis a computer program used to carry out ordination of vegetation data
DEM	Digital Elevlation Model (also known as DTM or Digital Terrain Model) a continuous raster layer in which pixel values represent elevation
dpi	dots per inch
Ecotone	the smallest possible land unit that is a holistic unit
Ecotope	the smallest homogenous mappable area of land
EMR	electro magnetic radiation
Exterior species	species primarily located at the edge of a landscape element
Gochar	a formation comprised of conglomerates and sandstone found in the field area
IFOV	instantaneous field of view
Interior species	a species located primarily away from the edge of a landscape element
IR	infra-red
Landscape	a heterogenous land area composed of a cluster of interacting ecosystems. Landscapes vary in size from 100s km to a few km in diameter
Landscape ecology	the study of the structure, function and change in a landscape
Landscape element	the basic, relatively homogenous ecological unit at the scale of the landscape
Los plasticos	large plastic greenhouses found in Almería used for intensive raising of salad crops using irrigation
Matrix	the most extensive and connected landscape element playing a dominant role in the functioning of the landscape
Mattoral	also known as maquis. A drought resistant Mediterranean scrub
MRU	Messinian Rich Unit: a part of the Gochar formation sourced from Messinian rocks which is younger than the TRU
NDVI	normalised difference vegetation index. NDVI finds areas of vegetation in imagery
Orthoimage	an aerial photograph or other remotely sensed image which has been transformed to conform to a map system using orthrectification
Orthorectification	a form of image rectification that corrects for terrain displacement

Patch	a nonlinear surface area differing in appearance from its surroundings
Quadrat	a basic sampling unit of vegetation surveys. Size is dependant on what is to be sampled.
Rectification	the process of making image data conform to a map projection system
Regadio	agriculture carried out in semi-arid Spain using irrigation
Secano	agriculture carried out in semi-arid Spain without irrigation
Sorbas member	a chalky limestone found in the field area
Training Area	an area of ground sampled to enable determination of clustered imagery. In this study the training areas were 15x15m to ensure complete 5m pixels of the ATM data were sampled
TRU	Triassic Rich Unit: a part of the Gochar formation sourced from Triassic rocks which is older then the MRU
TWINSPAN	Two Way INdicator SPecies ANalysis - a computer program used to carry out classification of vegetation data

1 CONTROLS ON LANDCOVER PATTERNS IN TWO ADJACENT STREAM CATCHMENTS IN SOUTH-EAST SPAIN

1.1 Introduction

> "Landscape development or formation results from three mechanisms operating within a landscape's boundary: specific geomorphological processes taking place over a long time, colonisation patterns of organisms and local disturbances of individual ecosystems over a shorter time" (Forman and Godron, 1986 p. 11)

The study of the ecological effects of the spatial and temporal distribution of different structural components or landcover units within a landscape is known as landscape ecology. Definitions of landscape ecology vary between authors. Zonnveld (1979) defines landscape ecology as an aspect of geography which sees the land as an holistic entity made up of differing parts, all influencing each other. Forman (1995 p. 45) simply describes landscape ecology as " the ecology of landscapes". Landscape ecology crosses the boundaries of disciplines and has the effect of filling some of the gaps between the various disciplines involved (Naveh, 1989). Landscape ecology differs from ecology in that whereas ecology has always sought spatial homogeneity for ease of analysis, landscape ecology sees spatial heterogeneity as a central causal factor in ecological systems (Pickett and Cadenasso, 1995).

Landscape ecology focuses on three characteristics of a landscape; structure, function and change (Forman and Godron, 1986). Structure is the spatial relationships amongst the elements present in the landscape; the distribution of energy, materials and species in relation to the shapes, sizes, numbers, kinds and configurations of the ecosystem. Function comprises the interactions amongst the spatial elements: the flows of energy, material and species between the components of the landscape. Change is the alteration in the structure and function of the ecological mosaic over time (Forman and Godron, 1986). There is a strong correlation between ecological pattern and ecological process (Gustafson, 1998) and by quantifying the landscape pattern, the processes at work in the landscape can be inferred.

This thesis attempts to apply a landscape ecology approach to an investigation of controls on two adjacent stream catchments in an area covering 1.6 x 2km of the Sorbas Basin in Almería province, SE Spain. The Sorbas Basin lies within a semi-arid area, one of the driest in Europe with an average rainfall of approximately 325mm (Capel Molina, 1990). This low rainfall total is reflected in a sparse plant cover which is generally composed of Mediterranean and Northern African species.

Geologically, the Sorbas Basin is part of the Internal Betic Zone which is composed of mountainous areas interspersed with depositional basins (Weijarmars, 1991). The study area contains parts of two adjacent catchments, the Barranco del Mocatán and the Barranco del Infierno, both of which drain into the Rio Aguas, the major drainage system of the Sorbas basin. The catchments represent different stages of an erosion-stabilisation cycle driven by base level change on the Rio Aguas caused by a river capture event which occurred approximately 100 000 years ago (Harvey and Wells, 1987, Harvey *et al*, 1995). The Infierno drains into the Rio Aguas approximately 7km above the capture site while the Mocatán drains into the Rio Aguas some 13km above the capture site. The capture-induced wave of erosion first worked its way up the Barranco Infierno causing incision and erosion followed by a period of stabilisation, and has more recently reached the Mocatán catchment which is currently experiencing severe erosion (Mather, 2000).

The fundamental question addressed by this thesis is as follows: are the differing patterns of landcover in the two study catchments a direct response to spatial and temporal patterns of geomorphological activity? The Mocatán catchment appears to be experiencing loss of original plagioclimax vegetation due to active erosion whilst the Infierno catchment has experienced a limited degree of vegetation gain during restabilisation. To investigate the differing landcover patterns in the catchments, and therefore the controls on these patterns, quantification of the cover is necessary, along with the measurement or derivation of a number of environmental variables.

1.2 Aims

The aims of this thesis are as follows:

To investigate relationships between environmental variables and landcover pattern in the study catchments in order to identify the major controls on landcover pattern.

To assess the utility of a landscape ecology approach for investigating the underlying controls on vegetation cover patterns in a semi-arid area

The first step taken towards these aims is the collation of information regarding the variables which may affect landcover pattern. This includes information about the climate of south-east Spain, recent geological and geomorphological history of the Sorbas basin and human activity within the basin. The literature regarding the effects of aridity on plant cover and plant species found in Almería is reviewed, along with that concerning human land use in Almería focusing on the effects of agricultural terracing. Field survey methods carried out to investigate ground cover and plant species found in the study area are described, as is the use of these data to provide ground truth information for training remotely sensed data. The vegetation data were analysed to explore patterns within them, and their relationship with other environmental variables. Aerial photographs of the study area were ortho-rectified to produce geo-corrected images conformable with the UTM map projection. A digital elevation model (DEM) was produced from aerial photography to allow the derivation of environmental variables such as slope and aspect. Airborne Thematic Mapper data were also processed and a Normalised Difference Vegetation Index (NDVI) was produced for classification purposes. The cover classes were used as input into a landscape metrics package and a Geographical Information System to quantify the pattern of landcover. The output metrics were then related to environmental variables in order to evaluate the controls on landcover patterns in the two catchments.

1.3 Objectives

1. To investigate plant cover and species in the study area using botanical field survey and vegetation analysis techniques.

2. To integrate remotely sensed data with data collected in the field to identify landcover patterns in parts of two adjacent stream catchments

3. To use aerial photography to derive a Digital Elevation Model (DEM) of the study area and from the DEM derive slope, aspect, and wetness index images.

4. To use Airborne Thematic Mapper (ATM) data to derive a NDVI to create an image showing the amount of photosynthetically active vegetation in the study area. Classify the NDVI image to create a simplified cover map of the study area showing green vegetation density to enable investigation of the landcover patterns.

5. To use a landscape metrics software (FRAGSTATS) and buffering of NDVI classes to quantify landcover patterns and as a basis for their analysis in relation to environmental variables.

1.4 Methodology

This research covers many different subject areas and techniques from vegetation analysis through remote sensing to the use of landscape quantification metrics, taking in geology, geomorphology, climate and botany on the way. As such, it falls squarely in the field of landscape ecology in its truest sense; that of a cross-disciplinary synthesis of techniques for investigation of landscapes and processes within landscapes. Applying FRAGSTATS and other landscape ecology methods to the question ‘what controls landcover pattern’ in a semi-arid area is a departure from the way that traditional remote sensing investigations of landscape are undertaken and is also a departure in the use of FRAGSTATS which is more often used in temperate areas to investigate interactions of wildlife with habitat. There are only a few investigations into landcover patterns in semi-arid areas using a landscape ecological approach (for example Carmel and Kadmon, 1999; Li *et al* 2001) and thus this research is applying well used techniques in a new environment.

The processing of remotely sensed data, and the collection of cover data from the field were means to an end, that end being the investigation of landcover pattern in the two study area catchments. Standard Geographical Information System techniques were used to extract data from remotely sensed imagery in order to enable the analysis of environmental variables which would be difficult and time consuming to measure in the field.

1.5 Data sources

Remote sensing resources used include aerial photographs (at 1:13 333) scale flown by the Natural Environmental Research Council in 1996 and Airborne Thematic Mapper data collected during the same flight (NERC ARSF Project 95/10). Mapping resources include geological maps (Mapa Geologico de Espana 1:50 000), paper topographic maps at 1:50 000 and 1:25 000 (Mapa Topográphico Nacional de Espana sheets 1031, 1031-I and 1031-III) and a digital topographic map at 1:10 000 (Mapa Topográphico de Andalucía Provincia de Almería).

1.6 Thesis outline

Chapter 2 introduces the field area. Semi-arid and Mediterranean climates are discussed with particular reference to the province of Almería in which the study area is based. Geomorphic processes in semi-arid areas are then examined. The recent geological history of the Sorbas basin is considered along with the geomorphological processes that have shaped (and are still shaping) the landscape. The characteristics of vegetation found in semi-arid areas are examined and the vegetation occurring in and around the study area in particular is described. Finally, a short history of human activity and its impact on the landscape in Almería is set out, with particular reference to the effect that agricultural terracing has on the environment.

Chapter 3 examines vegetation description and analysis techniques with emphasis on the techniques that were used whilst collecting data in the field area. The chapter then proceeds to report the results of the data collection. Vegetation ordination and classification techniques are examined with particular reference to those techniques used to analyse the data collected in the field area. Results of the analysis of the vegetation data from field area are then discussed.

Chapter 4 discusses photogrammetry and its use in producing rectified aerial photographs, DEMs and DEM-derived products. The rectification of the NERC 1996 aerial photographs, DEM production and derivation of the DEM products; slope, aspect and wetness index are all described.

Chapter 5 describes techniques that can be used for vegetation mapping and analysis using multi-spectral images. Image enhancement techniques are examined with particular reference to vegetation indices. Examples of the use of vegetation indices for vegetation analysis in semi-arid areas are given, concentrating mostly on the Normalised Difference Vegetation Index (NDVI). Ground truthing for guiding interpretation of imagery is discussed. The acquisition of data in 1996 for this thesis by the Daedalus Airborne Thematic Mapper is then reviewed with a discussion of the particulars of each band that was acquired. The methods used to analyse the data for investigation of vegetation in the study area are presented together with a discussion of classification techniques. An NDVI image of the study area is presented.

Chapter 6 discusses the selection of a clustered NDVI image for investigation of the landcover patterns and their interpretation in relation to the environmental variables aspect, slope and wetness. The process of selecting the most appropriate clustered image is described and the results of its analysis in relation to slope, aspect and wetness are presented.

Chapter 7 describes the main elements of landscape ecology and how they can be quantified using FRAGSTATS (a freeware landscape pattern quantification program). It then illustrates how FRAGSTATS and other techniques can be used to acquire landscape metrics for the clustered NDVI image of the study area and reports the results for these metrics and their interpretation.

Chapter 8 summarises the findings of the research and presents a summary of controls on landcover pattern in the two catchments with ratings of their relative importance.

Chapter 9 sets out how the aims of the thesis have been met, the major conclusions drawn and suggestions for further work.

2 AN OVERVIEW OF ENVIRONMENTAL PROCESSES ACTING ON SEMI-ARID AREAS WITH REFERENCE TO THE STUDY AREA

2.1 Introduction

This chapter introduces the field area. Section 2.2 considers, semi-arid, arid and Mediterranean climates in general and then proceeds to discussing the climate of Almería where the study area is based. Section 2.3 investigates the geomorphic processes acting on the landscape in semi-arid areas taking a particular interest in badland processes. The recent geological history of the Sorbas basin is then examined along with the geomorphological processes that have taken place (and are still taking place) to shape the landscape. Section 2.4 explores the vegetation found in semi-arid areas and discusses the vegetation in Almería province with specific reference to the Sorbas basin. Chapter 2 is concluded in section 2.5 with a short history of human activity in Almería province from prehistoric times until the present and its impact on the environment.

2.2 Climate

The study area lies within a zone that has characteristics of both Mediterranean climates and semi-arid/arid climates. Therefore both climate types are discussed below, followed by a description of the climate in south-east Spain and Almería province in particular.

2.2.1 Arid and semi-arid climates

Arid and semi-arid climates cover about a quarter of the Earth's land surface, and generally lie between 50º N and 50º S. However, warm arid and semi-arid regions are found mainly between 15º-30º latitude in both hemispheres. Koppen (1954) described the characteristics of arid and semi-arid climates as including low precipitation, high variability in precipitation from year to year, low relative humidity, high potential evaporation rates, clear skies, intense solar radiation, and high wind speeds. Evaporation is always higher than precipitation leading to a net deficit in available soil moisture.

Another climate classification was that by Meigs (1953) who produced a classification concerned with global food production potential. The classification was based on Thornthwaite's (1948) indices of moisture availability (Im): Im = (100S-60D)/PET where PET is potential evapotranspiration calculated from meteorological data, S is the moisture surplus and D is the moisture deficit aggregated on an annual basis (from monthly data) and taking soil moisture into account. Using this moisture availability equation Meigs (1953) defined three types of arid environment: semi-arid, arid and hyper-arid. Rainfall figures for semi-arid and arid areas were defined by Grove (1977) as 200-500mm and 25-200mm respectively. The UN's 1977 definition of aridity uses a P/PET index where P is annual precipitation and PET is potential evapotranspiration. Other definitions of aridity are reviewed in Thomas (1997). One of the only constants in arid areas is that precipitation totals frequently vary substantially from year to year and the only safe assumption is that any year could be extremely arid (Shantz, 1956).

2.2.2 Mediterranean climates

On the western side of continents between about 30º and 45º are found the Mediterranean climatic regions which have the relatively unusual combination of hot dry summers and cool wet winters. This climatic variation is caused by the poleward movement of a subtropical anticyclone over an ocean in the spring and summer which brings subsiding air into the region during the summer. Summers are characterised by clear skies and high temperatures. In winter, the anticyclone moves towards the equator and the subsiding air is replaced by frontal systems which bring precipitation. The amount of precipitation in Mediterranean areas generally varies between 350 to 900mm, with the lower amounts occurring in interior regions which border semi-arid regions

2.2.3 The climate of Almería, south-east Spain

The weather in European Mediterranean areas is dominated by the Azores anti-cyclone which produces climatic conditions similar to those described above in section 2.2.2. However, Almería's climate is much drier than would be expected simply from the effect of this anti-cyclone. Average rainfall at Almería Airport, recorded over a nine year period between 1981 and 1990 is 180mm per year. Figures for average precipitation measured at a meteorological station in Almería City give an average rainfall between 1951 and 1986 of 224.7mm (www.worldclimate.com, 2001). The average temperature at Almería Airport is 19.0°C and at Almería City is 18.1°C. These averages are taken over the same time periods as the rainfall figures (www.worldclimate.com, 2001) Monthly rainfall and temperature averages are shown in Figure 2.1 below

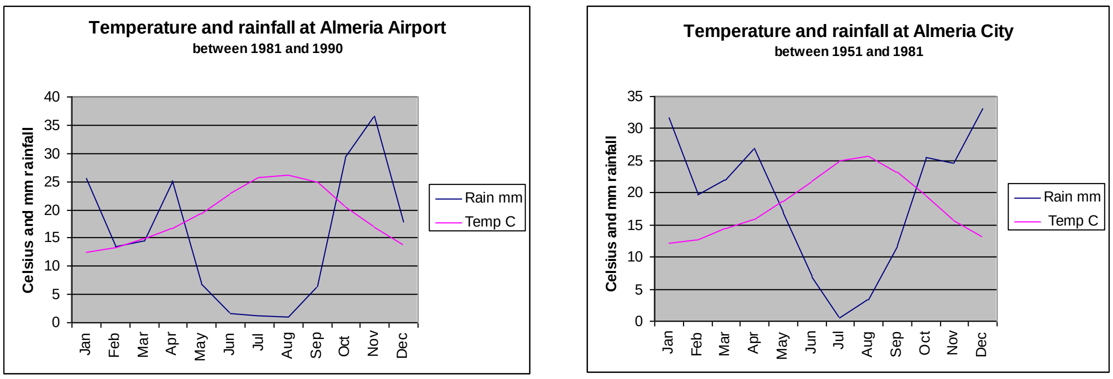


Figure 2.1 Average yearly temperature and precipitation in Almería

The unexpectedly low precipitation rate in the Almería region is caused by the rain shadow of the Sierra Nevada which adds to the already dry climate giving desert-like conditions in south-east Spain. This corresponds to a semi-arid climate type as described in section 2.2.1 or an arid classification according to Groves (1977) rather than a Mediterranean climate type or a wetter semi-arid definition of climate which is what would be expected from the latitudinal position of this area.

Rainfall in Almería is irregular and tends to occur in infrequent but heavy bursts (Capel Molina, 1990) The low average annual rainfall hides figures which indicate these sporadic periods of heavy precipitation. An example of this can be taken from two years of figures from the meteorological station at the Urra Field Centre (Fig 2.2) near Sorbas see which shows almost half the annual rainfall for 1996 occurring in just one month. Capel Molina (1990) records a 24 hour maximum rainfall of 150mm in Tabernas.

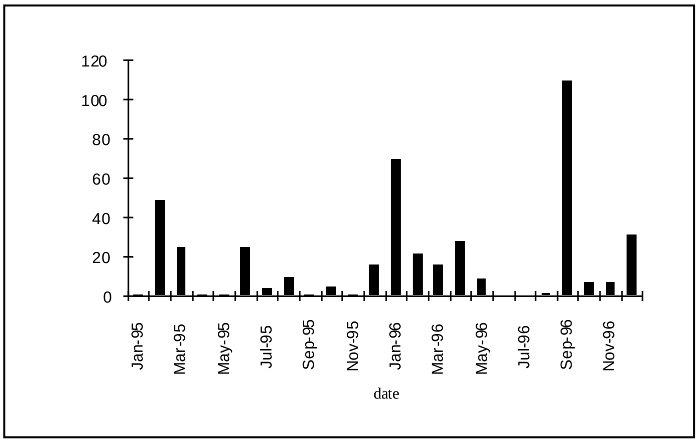


Figure 2.2 Monthly rainfall at Urra meteorological station 1995-1996 (Spivey, 1997)

Sole-Benet *et al* (1997) give figures for annual rainfall at the Tabernas meteorological station ranging between 115mm and 413mm over a 25 year recording period. The average annual rainfall at this station is 218mm and the annual number of days of rain at this station varies from 25 to 55. Figure 2.3 shows the frequency of rainfall events of a certain amount of precipitation per 1000 days from the Tabernas station over a period of 27 years (Lazaro and Puigdefábregas, 1994). It shows that out of every 1000 days there is likely to be a very high rainfall total (140-150mm) on only one of them. On 880 days out of 1000 there will be 0-10mm of rain.

The semi-arid climate of Almería is one of the most important factors in determining the geomorphological processes that take place, the vegetation that can survive in the environment and the human activities that take place. The geomorphological processes that take place in semi-arid areas are discussed next, and following that the geology and geomorphology of the Sorbas basin are discussed.

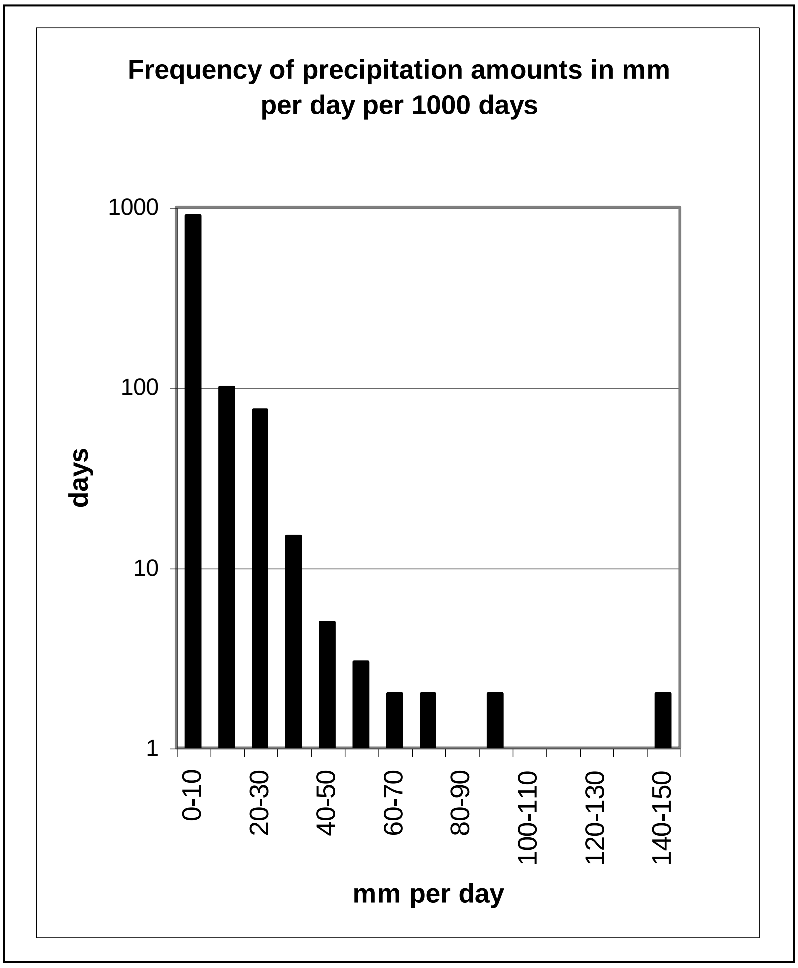


Figure 2.3 Frequency of precipitation amounts at Tabernas in mm per day per 1000 days (from Lazaro and Puigdefábregas 1994)

2.3 The geomorphology of semi-arid areas

2.3.1 Weathering

The causes of weathering in arid areas are many and complex, and there is no one single cause for all weathering. Rather there are a number of processes which act together to create the geomorphology of arid areas. Arid areas encompass a range of weathering environments by which means rock can be affected in a variety of erosion processes (Smith and Warke, 1997). Weathering in arid areas is a combination of some or all of the processes of insolation and thermal regimes; wind, moisture and precipitation, salt weathering and biotic weathering (Goudie, 1997).

2.3.2 Geomorphic form

Some attempts have been made to classify landforms present in some arid areas (Thomas, 1997). Obviously this type of generalisation has limitations, but it does demonstrate the importance of landscapes with high and frequent changes in relative relief, erosional and water-worked features.

Oberlander (1997) comments that as bedrock exerts a more direct influence over landforms in arid areas than in areas with soil-covered landscapes; slope forms in arid areas are diverse, related to the diverse underlying geological structures. Most of the landforms that dominate arid areas are the products of sporadic events that are widely spaced in time and intensity and are therefore rarely witnessed. The climates of the past 7000 years have been drier than previous climates in many arid areas over a period of several hundred thousand years which leads to the conclusion that many features in arid areas are relict and not formed under current climatic conditions (Oberlander, 1997). This is particularly true in some areas of the U.S. and South America for example, but is not the case in the Mediterranean margins (Harvey pers comm.). However, in all arid areas there are processes which happen over the short term. These include fluvial channel erosion, dune movement and badland processes which are discussed below.

2.3.3 Badlands

2.3.3.1 Badland definition

The word "Badland" is likely to be derived from the French *Terres mauvais a traverser* literally meaning land that is difficult to cross. *Terres mauvais* then being translated as "Bad lands" This term was coined during the nineteenth century by settlers moving into the American West to describe areas of Dakota and Utah where badlands were barriers to movement across the landscape. Badlands have little economic value due to their instability and barren nature (Campbell, 1997).

Campbell (1997) suggests that badlands can develop in a range of materials and environments globally, but they are most often associated with arid and semi-arid climates characterised by infrequent but intense rainstorms. In these areas badlands tend to develop in areas with soft, horizontally bedded, relatively impermeable rock which is exposed to rapid fluvial erosion. Howard (1994) describes badlands as having little vegetation, steep slopes, high drainage density, shallow to non-existent regolith, and rapid erosion rates. Bryan and Yair (1982) describe badlands as being intensely dissected natural landscapes where vegetation is sparse or absent and which are useless for agriculture. Badlands are characterised by very high drainage densities, V-shaped valleys and short steep slopes often fringed by gently sloping planar surfaces referred to as pediments.

Bryan and Yair (1982) expand this definition of badlands to include large areas, particularly in semi-arid regions where a fragile natural equilibrium has been disturbed by ill-advised land use practices causing the delicately balanced system to move swiftly into badland degradation. Campbell (1997) also refers to a lack of vegetation as an important characteristic and describes badlands as barren. Alexander and Calvo (1990) disagree with the idea that badlands are unvegetated, and comment that biological activity as well as being present in badlands significantly affects the geomorphic processes and landform evolution.

2.3.3.2 Badland morphology

A typical badland in a semi-arid area would consist of steep sided upper slopes above gently sloping pediment surfaces. Badlands generally have very complex microrelief consisting of pipes, rills gullies, desiccation cracks, sharp divides and vertical faces (Campbell, 1997). The geometry of slopes in badland areas reflects lithological control where more permeable slopes slide en-masse whilst saturated, whereas less permeable slopes rill and gully (Schumm, 1956) and slopes with high sodium ion content will tend towards piping (Heede, 1971) forming the characteristic badland morphology. According to Campbell (1997) badland erosion is controlled by regional geological conditions. However, an area of badlands will not erode in an homogeneous manner, there will be local variations in rate and type of erosion which represent site-specific environmental controls. Spivey (1997) produced a comprehensive review of badland literature where the characteristic forms are utilised as a means of categorising and describing badlands on the basis of macro, meso and micro morphology along with material characteristics which affect the micro morphology of badlands.

2.3.3.3 Rills and Gullies

Howard (1994) describes the three different types of surface channel that transport water in badland areas as cracks, rills and gullies. Runoff in badland areas concentrates in cracks, micropipes and ephemeral rills and does not exhibit the classic overland flow characteristics (Howard, 1994). In a review of the literature on rainsplash and rill initiation Howard (1994) comes to the conclusion that runoff is capable of detachment of sediment and rill initiation on most badland surfaces. Creation and obliteration of rills in semi-arid areas can happen during a single heavy rainfall.

Bocco (1991) defines gullies as channels whose width and depth do not permit tillage, with a depth of 0.5m used to differentiate them from rills. Bocco also describes how gullies can enlarge by the processes of basal cutting, headcut retreat due to runoff, headcut retreat due to seepage and undercutting, and head and side wall collapse due to cracking and positive pore water pressure build up. Gullying is a major mechanism in badlands formation, especially when associated with mass movement (Beaty and Barendregt, 1987)

2.3.3.4 Piping

Piping is a type of erosion where material is carried away by water through holes in the ground (Heede, 1971). The hydrological significance of pipes is that they form a separate drainage system which can transgress topographical divides (Campbell, 1997). Badland areas often, but not always have pipes and there are according to a review by Campbell (1997) at least seven different basic conditions necessary for piping. These include strongly alternating wet and dry climatic patterns (preferably with some intense rainstorms); deep desiccation cracking or other fractures for entry of moisture; steep slopes providing sufficient hydraulic head to assist subsurface flow; presence of swelling clay minerals and large amounts of exchangeable sodium; alternating units of permeable and impermeable strata; and an outlet for the pipe system. Pipes may also develop on subhorizonal surfaces of abandoned agricultural land (Martin-Penela, 1994; Thompson and Scoging, 1995). Pipes are known to have an influence on the origin and development of gullies (Martin-Penela, 1994) where, for example, pipe collapse leads to gully formation. Harvey (1982) described 3 main different types of piping in a study of badland sites in south-east Spain.

1) Shallow pipes which are irregular in section and never more than a few cm in diameter.
2) Deep pipes from 0.5 to several metres below the surface which occur in several forms:
a) Pipes developed by the removal of weak material from below lightly crusted surfaces
b) Deep pipes developed in relation to differential porosity, cementation or solubility within the material.
c) Deep pipes formed in relation to tension cracks in thick silt formations.
3) Bridge piping where entrenchment or undercutting form an overhang which on collapse may create a bridge over a gully floor.

2.3.3.5 Aspect controls

Aspect is one of the most important factors in the differences of form of differently oriented slopes in mid and high latitudes. Churchill (1982) found that north-facing slopes in South Dakota, U.S. had a higher drainage density than south-facing slopes which attested to the relative importance of wash and gullying on the north facing slopes. Churchill (1982) investigated differences in moisture content of north- and south-facing slopes and concluded that south-facing slopes were generally drier and also subjected to more intense periods of wetting and drying which triggered small rockfalls, leading to a practically non-existent regolith. North-facing slopes in contrast have higher moisture levels (accounting for the higher drainage density) leading to dissolution of binding cements and therefore thicker regolith which in turn can lead to more erosion due to the easy removal of the weathered material if it has not been stabilised by a stone cover or a form of organic crust (Alexander *et al*, 1994). Howard (1994) found that badland regoliths in arid regions can range from about 300 mm to essentially unweathered bedrock, but Lazaro *et al* (2000) report regolith depths of over 1500 mm in the Tabernas badlands in south-east Spain.

2.3.3.6 Badland evolution and stabilisation

An area which has some of the characteristics of a badland e.g. soft, impermeable sediment may not become a badland until there is the right trigger. This may be climatic change bringing heavier rain or a decrease in vegetation cover through grazing or for other reasons such as fire. Another trigger is the lowering of the channel base due to a change in the profile of the river the area drains into (Howard, 1994). Howard (1994) has developed a model imitating a scenario where the downstream end of a flat alluvial deposit undergoes a lowering due to a base-level change, which then stabilises. Figure 2.4 shows a model (Howard, 1994) of successive stages of dissection of an alluvial surface which is grading towards the new lower river level.

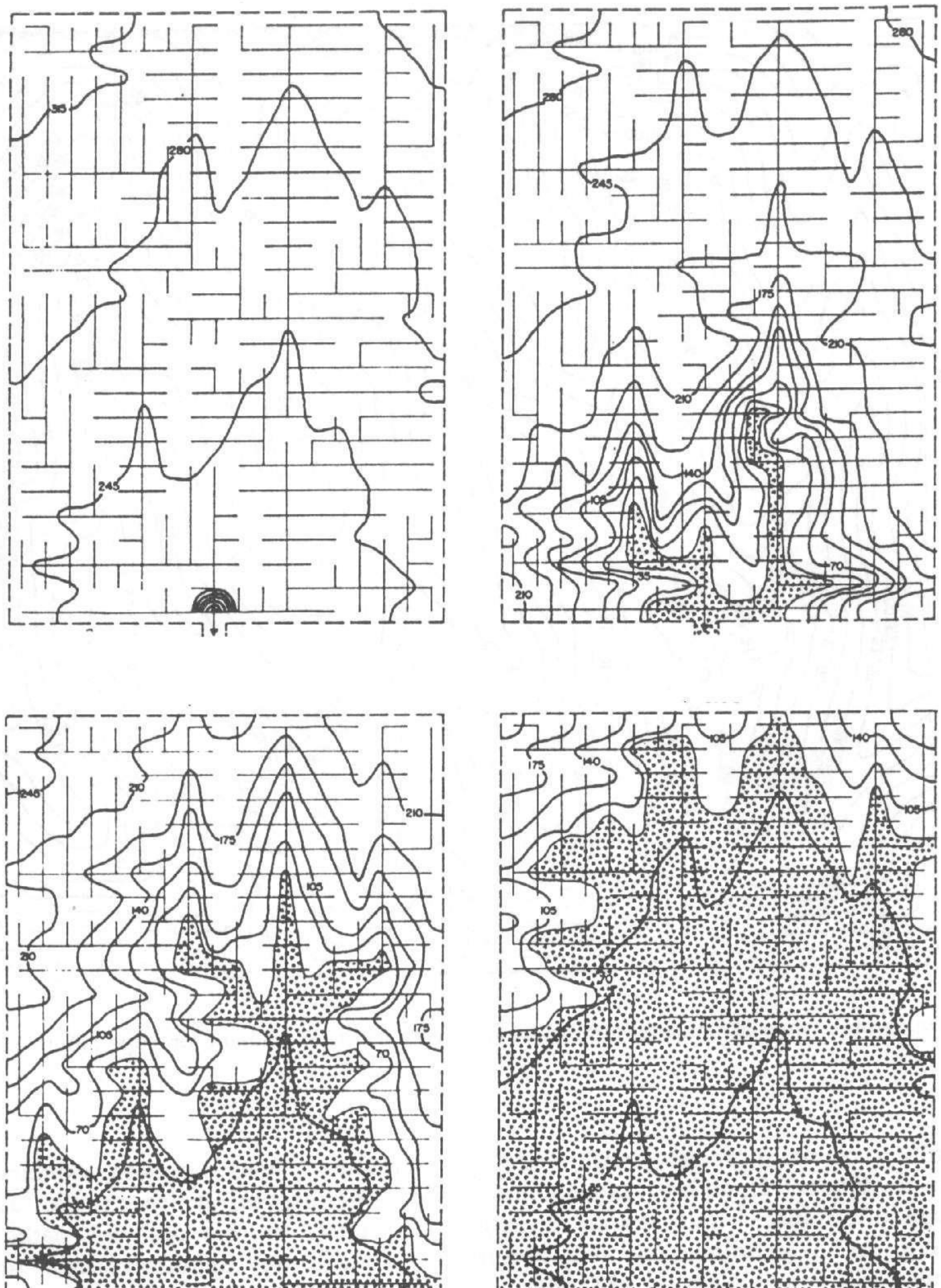


Figure 2.4 Successive stages in the dissection of an alluvial surface after an instantaneous lowering of the downstream end of the basin followed by stability (Howard, 1994)

A characteristic of unstabilised badland areas is the speed of change in these landscapes. Fine-scale features in badlands have short reaction times and may adjust their forms rapidly, for example an individual rill may lose sediment after medium intense rainfall (Campbell, 1997; Spivey, 1997). Erosion in badlands is limited only by the frequency and magnitude of rainstorms, and there is what seems like an endless supply of material to be washed downslope. (Campbell, 1997) This material is generally quite fine grained - a mixture of silt and clay particles with various cementing agents (e.g. iron oxide and calcite) playing a role in the behaviour of the sediment.

A particularly important role is played by sodium ions which have the effect of deflocculating clay particles making the sediment more prone to erosion, especially to piping. Breazeale (1926) demonstrated that the amount of erosion on a site will increase where sodium is present as the sodium increases the dispersivity of soils. Benito *et al* (1992) found that the physico-chemical properties of materials were diagnostic of badland morphology with different levels of sodium cations in the sediment leading to different morphologies, with or without pipes. According to Barendregt and Ongley (1977) the presence of montmorillonite (a sodium clay) is an *a priori* factor in piping and Heede (1971) states that piping soils have a higher exchangeable sodium percentage and sodium adsorption ration than non-piping soils. Heede (1971) suggests that leaching of sodium ions from topsoil will cause an increase in pH which will make calcium more available to plants and vegetation will eventually become established, helping to stabilise the gully sides. Alexander *et al* (1999) demonstrate that surface samples of material taken from badlands are all less dispersive than subsurface material which would indicate that badland soils leech their sodium and surfaces stabilise to some extent.

Badland slopes may eventually stabilise if the mechanisms of erosion are reduced sufficiently. Recent work has identified the fact that badlands are shaped by multiple processes and erosion rates may change as process interactions change, which may ultimately result in badland processes ceasing altogether (Alexander *et al,* 1994). Campbell (1989) postulates stabilisation resulting from progressive slope angle reduction during slope erosion, Poeson (1990) considers the development of a stone cover to be an important factor in badland stabilisation, Alexander and Calvo (1990) and Thornes (1990) consider lichen and the colonisation of higher plant species to be factors in badland stabilisation. Faulkner's (1990) results indicate that bare areas will generate runoff during rainfall events, but areas that are vegetated do not produce runoff in 'normal' rainfall events adding weight to the hypothesis that ground cover prevents erosion. It would seem that there is a natural negative feedback mechanism that reduces erosion rates on badland surfaces following a reduction in basal incision or basal removal of sediments. The effectiveness of this stabilisation mechanism is increased where there is cover on the surface (Alexander *et al,* 1994).

Examples of the above are Yair *et al* (1980) found that the badlands in the Negev desert evolved rapidly 70-40,000 years ago, but have been minimally eroded in the past 20,000 years. Alexander *et al* (1994) found that in the Tabernas badlands in south-east Spain, natural stabilisation is taking place due to stone armoured and lichen covered surfaces. However, these stabilisation sequences may be broken due to tectonic or climatic factors in the long term, or in the shorter term due to hydrological or ecological change in response to human interference, climatic fluctuations or threshold-exceeding storms (Alexander *et al,* 1994).

2.4 Geology of the Betic Zone, Spain

The study area lies within the Betic Cordilleras of the Iberian Peninsula (see Figure 2.5). According to Fallot (1948) the Betic Cordillera can be divided into an External Zone to the north and an Internal (or Betic) Zone in the south (see Figure 2.5). The main interest in this thesis lies in the Internal (or Betic) Zone. This Zone comprises mainly Triassic and older clastic metasedimentary rocks exposed in thrust nappes (Weijermars 1991). Faulting has produced a series of uplifted mountain ranges between which are sedimentary basins, infilled by Neogene sedimentary rocks (Weijermars 1991). The Sorbas basin comprises one of these sedimentary basins. The details of the early formation of this mountain and basin geological landscape is beyond the scope of this thesis and reviews of the aggradational sequence can be found in Weijermars (1991).

2.4.1 The geology and structural setting of the Sorbas basin

The Sorbas basin is a depositional basin within the Betic Cordillera. It is bounded on the north by the Sierra de los Filabres and on the south by the Sierras Alhamilla and Cabrera and on the west it is divided from the Tabernas basin by a low level watershed (Figure 2.6). A major reverse fault delimits the northern side of the Sierras Alhamilla and Cabrera to the south of the basin. In the Sorbas basin the Messinian-Pliocene rocks are folded into E-W folds along a syncline (Figure 2.6) creating a distinct inner basin bounded by steeply dipping Messinian rocks to the south (Harvey, 1987). The southern margin has been most active during the Sorbas basin's development and is associated with the strongest deformation. It is currently the focus for differential epeirogenic uplift as a result of nappe emplacement and the compressional regional tectonics(Weijermars *et al,* 1985), some 600m of which has occurred since the mid Pliocene (Harvey and Wells, 1987: Mather, 1993).

The basement rock consists of metamorphic rocks including carbonates from the Internal Betic Zone comprising Alpujarride and Nevado-Filabride rocks (Weijermars, 1991; Martin and Braga, 1994). The Alpujarride Complex is dominant in the southern margins of the basin in the Sierras Cabrera and Alhamilla, and the Nevado-Filabride Complex is dominant in the Sierra de los Filabres in the north. Alpujarride materials comprise black graphite schist, low grade metamorphic and Triassic carbonate rocks, phyllites and quartzite (Platt, 1982; Kozur *et al,* 1974; Egeler and Simon, 1969). The earliest deposited sediments within the Sorbas basin are pre-Tortonian conglomerates which are unconformably overlain by Tortonian (Upper Miocene) sediments. These demonstrate shallow water facies adjacent to the Filabride uplift and deeper water marls and turbidites in the south of the basin (Weijermars, 1991). These sediments were folded and compressed as a by-product of the Alhamilla/Cabrera uplift (Weijermars *et al,* 1985).

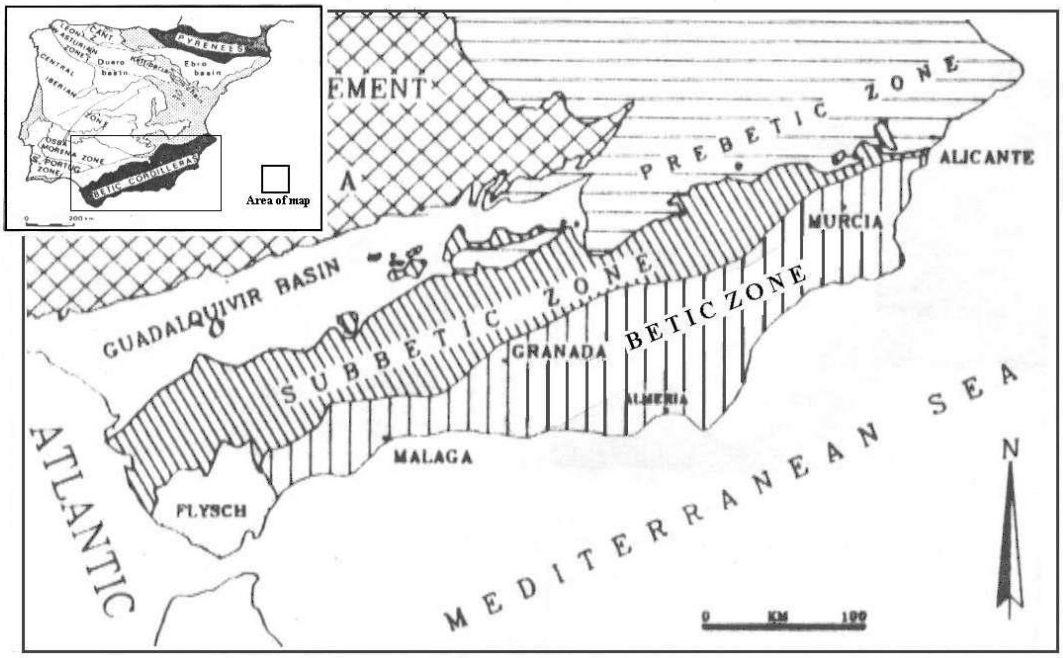


Figure 2.5 The Betic Cordillera (modified from Weijermars, 1991)

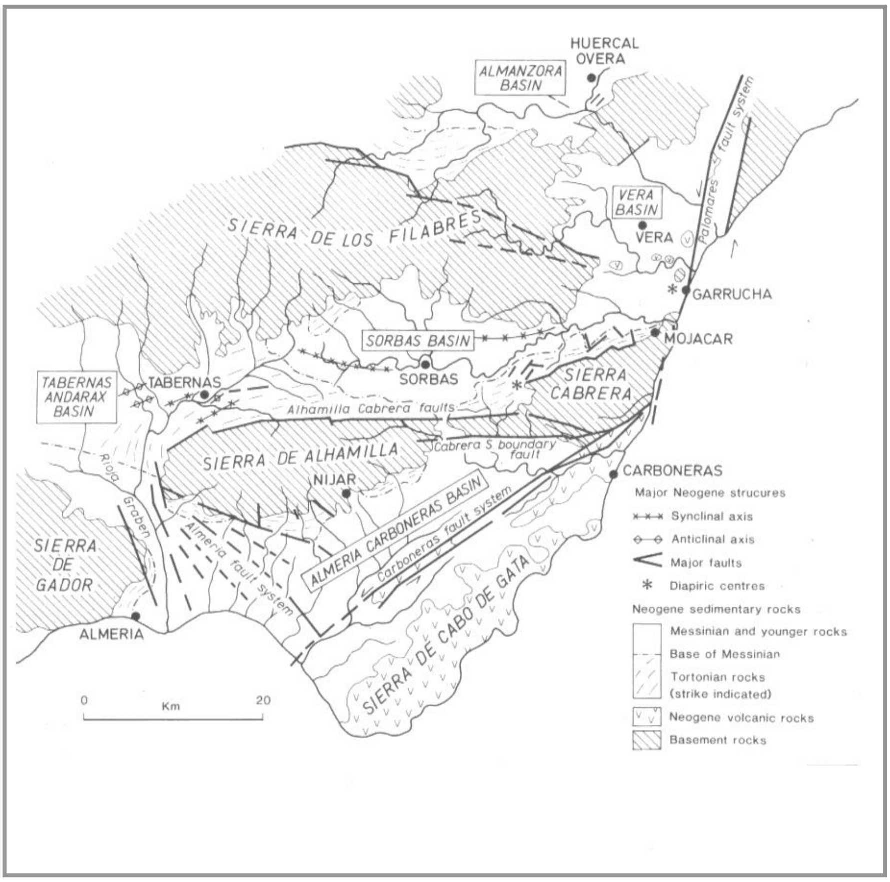


Figure 2.6 Major tectonic features in and around the Sorbas basin (Harvey, 1987)

The Messinian (Upper Miocene) sediments rest unconformably on the underlying sediments indicating a break in marine deposition coincident with the end of Tortonian tectonic activity (Figure 2.7). However, as the sediments show, marine conditions returned and the depositional environment was re-established. The sequence shows calcarenite (the Azagador Member) followed by reef limestone (the Cantera Formation) and marls (the Abad Marl formation). These deposits were followed by a deposit of gypsum (the Yesares Member) laid down during the Messinian Salinity crisis, a period of time when the Mediterranean shrunk in extent 7-5 Ma B.P due to loss of connection with the Atlantic (Weijermars, 1991). This formation is described in much greater detail in Weijermars (1991).

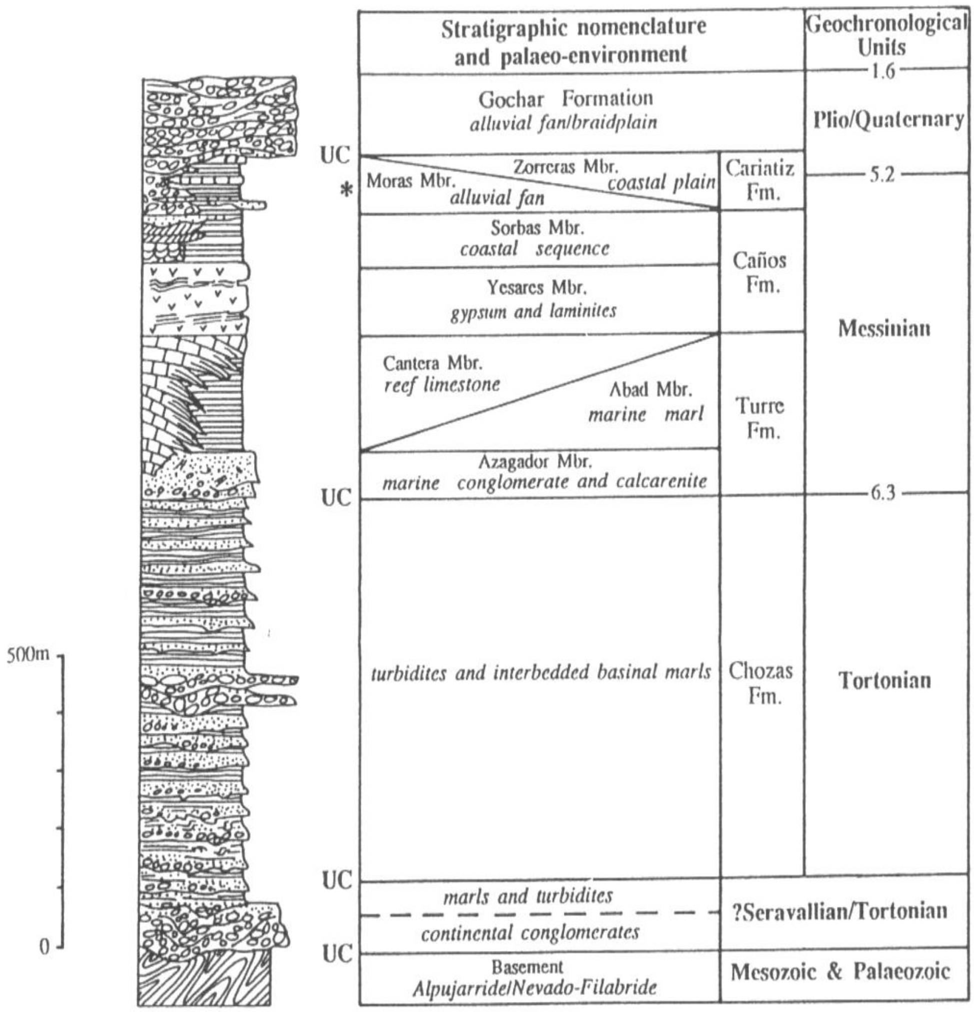


Figure 2.7 Neogene stratigraphic column for the Sorbas basin (From Mather and Harvey, 1995) UC indicates unconformities.

After the Messinian Salinity Crisis a marine connection with the Mediterranean was re-established in the Sorbas basin. This is evidenced by a regressional sequence of shallow marine sediments (Sorbas Member chalky limestones). Epeirogenic uplift lifted the basin above sea level so deposition of the Sorbas Member was followed by deposition of coastal terrestrial sediments with minor marine incursions, these terrestrial sediments forming the Cariatiz Formation comprising the Moras Member alluvial fans and Zorreras Member floodplain sediments (Roep *et al*, 1979; Mather, 1991). There is also evidence of a brackish lake which stretched across the Sorbas basin on two occasions, with variations in the facies and microfossils indicating a marine connection to the south (Mather, 1993) A geological map of the Sorbas basin can be found in Figure 2.8.

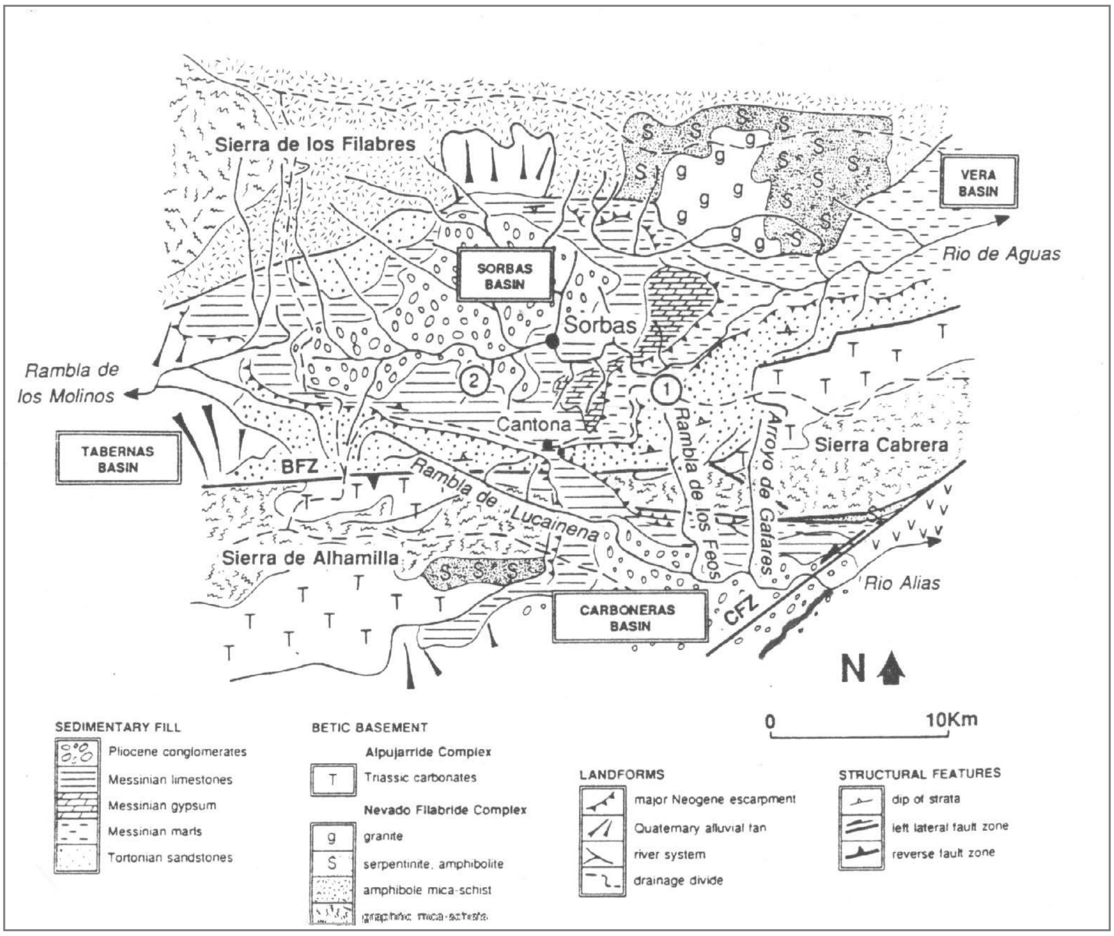


Figure 2.8 Geological map of the Sorbas basin and surrounding area (from Mather, 1993)

2.4.2 Drainage development, the Gochar Member and river terrace deposits

The marine withdrawal from the Sorbas basin due to tectonic uplift left a gap in the Sierra Alhamilla through which the consequent Plio-Quaternary drainage network that developed would drain the basin (Harvey and Wells, 1987). According to Mather and Harvey (1993) small alluvial fans developed along the margins of the Sorbas basin, and with continued drainage development these conglomerates prograded from the basin sides across the entire basin producing the conglomerates and sandstones that comprise the Gochar Formation. Mather (1993) distinguishes four drainage sub-systems within the Gochar Formation conglomerates. Two drain from the north (A and B in Fig 2.9), one from the south (D) and one drains the centre (C) of the basin from west to east. It is the Mocatán System, the sub-system which drains from the south (D) that contains the study area for this thesis.

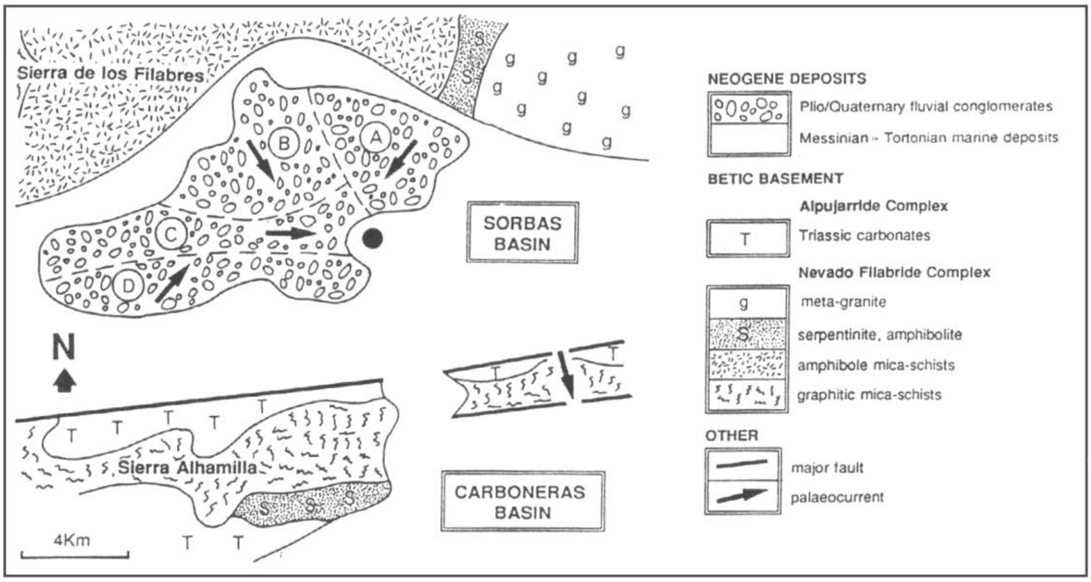


Figure 2.9 Distribution of the main fluvial systems identified within the Gochar Formation of the Sorbas basin (from Mather and Harvey, 1995)

There were three stages of deposition of the Gochar Formation. Early Gochar deposition was dominated by silts and sands which were fed into the central part of the basin by palaeochannels (Mather, 1991). This evidence comes mainly from the north and centre of the basin, although in the Mocatán System there is a dominance of sandstone in the lower reaches which suggests a similar depositional environment with deposited sediments prograding into a small lake system comprising shallow water bodies (Mather, 1991). These lakes were ephemeral as the sediments deposited into the lakes were exposed to pedogenesis (Mather, 1991).

A noticeable prograding of the fluvial systems marks the Middle Gochar deposits. This is characterised by a coarsening of material deposited. In the Mocatán System in the SW of the basin a bajada was fed by small fans, contributing sediment to shallow ephemeral channels in the distal parts of the system (Mather and Harvey, 1993). The Late Gochar deposits show the fluvial systems at their maximum development.

2.4.3 Modification of the Gochar deposits in the Mocatán System

Two distinct units of sedimentary material comprise the Gochar Formation in the Mocatán System; the Triassic Rich Unit (TRU) being the lower and the Messinian Rich Unit (MRU) the upper. They are separated by a weak unconformity (Mather, 1993). Of the two units, the TRU dominates, especially in the west of the Mocatán System where it makes up 95-100% of the total sediment in the Gochar Formation. In the east of the Mocatán System the TRU accounts for about 80% of the total sequence with the top 20% of the sequence being comprised of MRU (Mather, 1993).

The composition of the two units indicate they have different source areas. The TRU's sediment content indicates a source rich in supply of Tortonian sandstone and Triassic limestone. The most obvious source for this material is the northern side of the Sierra Alhamilla where Tortonian sandstone is available, as is Triassic limestone. The TRU deposits are thick and were laid down fast which is evidenced by the absence of any well developed soil horizons (Mather, 1993). The MRU comprises a clast assemblage dominated by Messinian limestone and lacking in Triassic carbonate limestone and containing a much reduced amount of Tortonian sandstone compared to the TRU. This implies a change in source area geology as there is no evidence of material from the Sierra Alhamilla in the clast assemblages. Reduced rates of sedimentation and increased pedogenesis are also evident implying a smaller catchment area with less water and sediment supply (Mather, 1993).

Mather's (1993) conclusion from this evidence is that the initial supply of sediment to the Mocatán System was cut off when the Rambla de Lucainena, a subsequent river system draining across the front of the Sierra Alhamilla, captured the south-north palaeo-Mocatán drainage from the Sierra Alhamilla (Mather and Harvey, 1993). This process is shown in Figure 2.10. TRU material could no longer reach the Mocatán System as the capture took all the drainage that had carried the sediment. The MRU material deposited after this capture came from the Messinian reef limestone ridge that forms the watershed between the Mocatán System and the Rambla de Lucainena to the south. This cutting off of the major sediment supply explains the reduction in sedimentation that the MRU demonstrates. It also explains why there is more MRU in the east of the Mocatán System. As the Rambla de Lucainena progressively captured streams in an east-west direction, so gradually cutting off supply, there was more time for deposition of TRU material from the Sierra Alhamilla in the west. The Gochar sequence in the Mocatán System is capped with a calcreted erosional surface at about 500m in height which may grade into Harvey *et al*'s (1995) River Terrace A (Mather and Stokes, 1996).

2.4.4 River terrace gravels, river capture and the development of the present day Sorbas basin drainage system

The proto-Feos drained the Sorbas basin into the Carboneras Basin during the early and mid-Quaternary. The nature of this drainage was centripetal with channels from the mountains to the north and south of the Basin draining into a central river channel which then flowed south through a gap in the Alhamilla-Cabrera range (Harvey and Wells, 1987; Harvey *et al*, 1995; Mather and Harvey, 1995). As discussed above, the first recorded river capture in the Sorbas basin was the capture of south-north draining streams by the Rambla Lucainena which diverted approximately 15% of the original Sorbas basin drainage into the Carboneras Basin in the early Pleistocene (see Figure 2.8). Clast assemblage changes record this capture as described above and in Mather (1993). However the major capture affecting the geomorphology of the whole Sorbas basin was the capture of the main drainage, the proto-Feos by the proto-Aguas in the late Quaternary (Harvey and Wells, 1987; Harvey *et al*, 1995; Mather and Harvey, 1995).

The nature of incision by the Sorbas basin Quaternary river system was episodic. This is documented by a series of 4 main depositional terrace levels (A-D) and a smaller fifth deposit, E (Harvey and Wells, 1987; Harvey *et al*, 1995). Soil development on these terraces shows evidence of episodic depositional environments in the Sorbas basin (Harvey *et al*, 1995). Terrace stages A, B and C represent successive stages in the process of the proto-Feos incising the sediments in the Sorbas basin due to tectonic uplift (Harvey and Wells, 1987). Terraces A-C are cemented fluvial gravels resting unconformably on the underlying rocks. Soils on A and B show high levels of rubifaction indicating well developed soils. Stage C is less developed.

The differential uplift of the Sorbas basin has been centred around Cantona, a mountain on the Messinian reef limestone ridge in the south of the basin (see Fig 2.10). The relatively high rates of uplift in relation to neighbouring basins has accentuated the development of aggressive streams from the east and west of the basin which captured portions of the proto-Feos drainage. The largest and most spectacular river capture was that initiated by the proto-Aguas which worked its way westwards from the Vera basin along the strike of the weak Abad marls to capture the proto-Feos at the present day site of Los Molinos del Rio de Aguas (Harvey and Wells, 1987; Harvey *et al*, 1995). This capture re-routed approximately 73% of the original Sorbas basin drainage from the Carboneras Basin to the south into the Vera basin to the east (Mather and Harvey, 1995). The capture of the Sorbas basin drainage by the proto-Aguas occurred after the deposition of stage C gravels and before Terrace D was deposited which suggests an age for the capture of approximately 100 000 years ago (Harvey and Wells, 1987; Harvey *et al*, 1995).The capture of the Sorbas drainage by the Aguas left the Feos as a beheaded channel. The effect of the Rio Aguas capture on the headwaters of the Feos has been to change the base-level of the Sorbas basin drainage by 150m at Los Molinos del Rio del Aguas (Harvey, 1987; Harvey *et al*, 1995). There is about 90m of incision at Sorbas which is approximately 10 km upstream from the capture site. Upstream from Sorbas changes to base level fall to less than 40m in the little dissected upper basin (Harvey, 1987). Base-level change here has been inhibited by nick points due to lithological changes in the river bed ,Mather 2000).

The uplift of the Sorbas basin and subsequent capture of the main drainage had a profound effect on the drainage patterns in the basin above the capture site. Drainage in the Sorbas basin can be divided into four main types (Mather and Harvey, 1993). Original consequent drainage is found in areas which have suffered minimum impact from external controls. This type of drainage is mainly found in the north west of the Sorbas basin where tectonics and therefore river capture have had little effect. Transverse antecedent drainage has developed across the fronts of some of the mountain ranges, draining perpendicular to strike. They maintain their courses across axes of uplift as they incise at the same rate as uplift becoming superimposed on the structures. Examples can be seen in Figure 2.11 where the Rio Feos drains across the Sierra Cabrera and the Rio Jauto drains across the Sierra de los Filabres. Beheaded original consequents are channels which have had their headwaters removed by capture, suffering reduced sediment and water input. A prime example of a channel in this category is the Feos. Aggressive subsequents are those channels which have captured other channels (for example the Rio Aguas). Aggressive subsequent streams stimulate incision and are the agent of much of the incision currently taking place in the Sorbas basin.

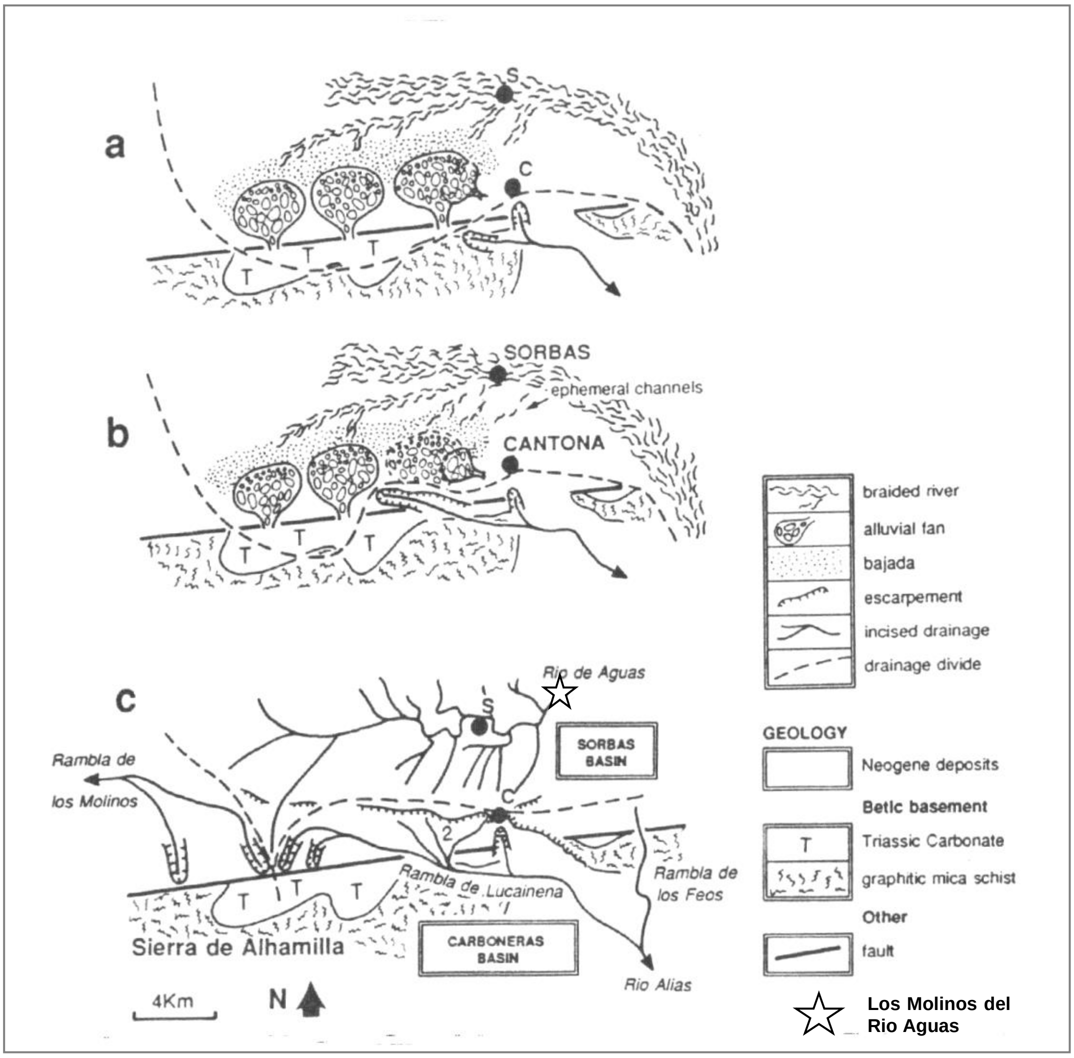


Figure 2.10 Diagram showing river captures in the Sorbas basin (modified from Mather, 1993) a) is the lower middle Gochar formation, development of the TRU. b) Upper Gochar formation – headward erosion of the Ramble de Lucainena beheading S-N drainage channels. Changes in clast formation are indicated by a dashed fan outline. c) Post Gochar formation where river capture by the Rambla de Lucainena has beheaded S-N drainage which fed the main Sorbas basin drainage. The Rio Aguas has captured the original basin drainage and established an incised drainage pattern replacing the original braided drainage.

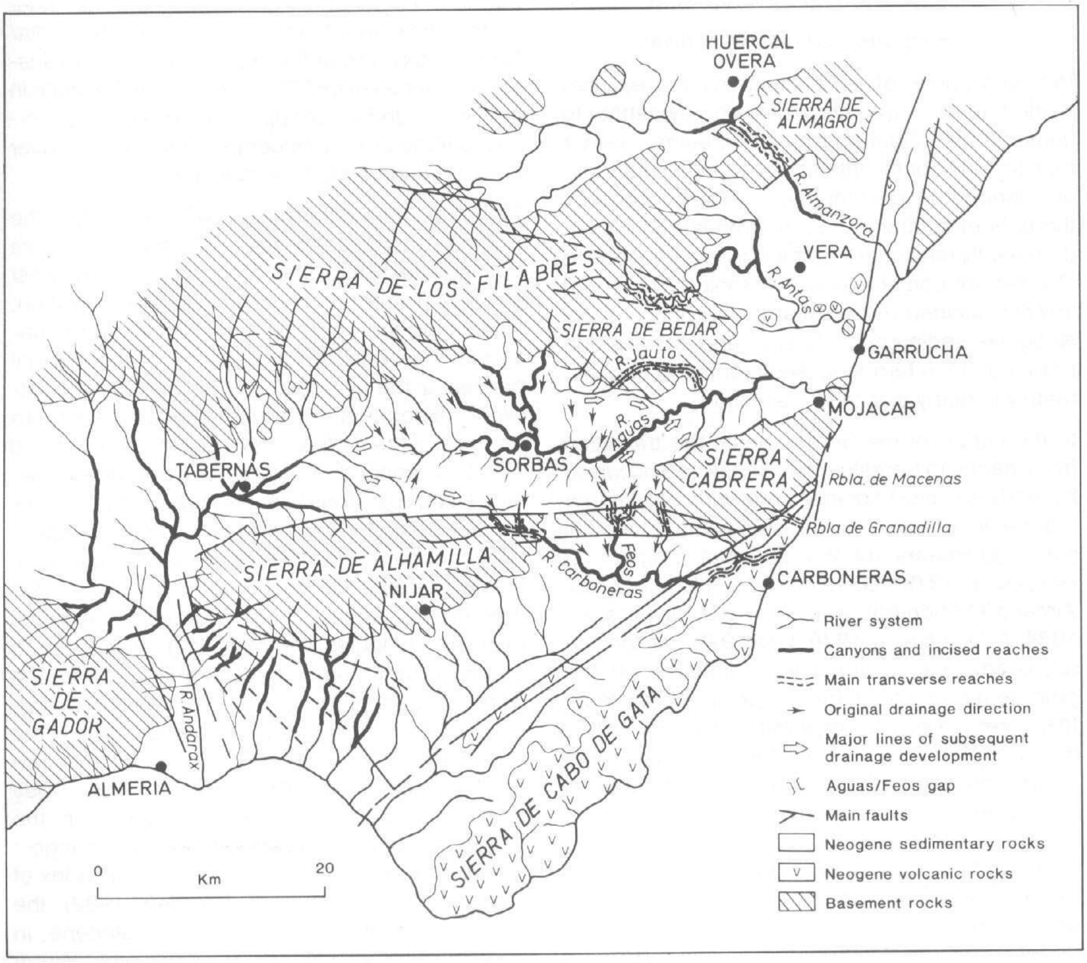


Figure 2.11 Current drainage in and around the Sorbas basin (from Harvey, 1987)

2.5 The study catchments

2.5.1 Drainage evolution in the two study catchments

According to Mather (2000) The Barranco del Mocatán and Barranco del Infierno incised approximately 40m below the Plio/Pleistocene surface in the time between dissection initiation and the end of Terrace C deposition (therefore prior to the capture of the Feos by the Aguas). The early drainage associated with the catchments was dominated by a S-N and WSW-ENE consequent drainage. Post capture, the original consequent drainage was truncated by the development of aggressive subsequent drainage initiated by the wave of incision from the capture point at Los Molinos del Rio Aguas. The subsequent streams developed first in the Infierno catchment as it was nearer the capture site and therefore reached by the incision first (see Figure 2.12 at 1).

The Infierno pirated many lesser streams which drained S-N into the Rio Aguas which led to a change from the original S-N drainage to a more WSW-ENE direction. It also appears to have pirated some of the original tributaries of the Barranco del Mocatán. The mouth of the Barranco del Mocatán (see Figure 2.12 at 2) was reached later by the wave of incision from the capture point at los Molinos and pirated back some of the river captures that the wave of incision up the Barranco del Infierno had made, leaving a series of obsequent streams and a slight change to the position of the watershed between the two basins. Mather (2000) suggests that this stage of drainage development is responsible for the gullied and piped badland landscape currently found in the mid-reaches of the Mocatán catchment. River piracy continues within the badland areas via piping and gullying and it appears that base-level change is still continuing in this section of the Barranco del Mocatán. Gully development in the Barranco del Mocatán lies along an E-W fault with dips of up to 70° in the beds of the Gochar material (Mather and Stokes, 1996)

2.5.2 Barranco del Infierno

The tributaries of the Barranco del Infierno catchment are sourced from the Cantona Ridge to the south of the Sorbas basin which divides the drainage of the Rambla Lucainena and the Rio Aguas. The Barranco del Infierno itself is a small stream which originates in the hills of the Malaguica area in the south of the Sorbas basin (Figure 2.12). The junction of the Barranco del Infierno and the Rio Aguas is about 7km above the Aguas/Feos capture site at Los Molinos. The Barranco del Infierno runs mainly through gypsum, Messinian limestone and marl. There is a small section, part of the Barranco de los Contreras, a tributary of the Barranco del Infierno (see Figure 2.13), which runs through Gochar material. Most of the river sections form incised canyons through the stronger lithologies of carbonate and gypsum. However, there are small areas of badland in Gochar material in the Barranco de los Contreras and consequently, a wider valley profile in the weaker Gochar material. Badland development in the Barranco del Infierno is of small extent but with a relative relief of 80m, rising out of the Barranco to the top of the hill La Cruz de San Marcos (Figure 2.12).

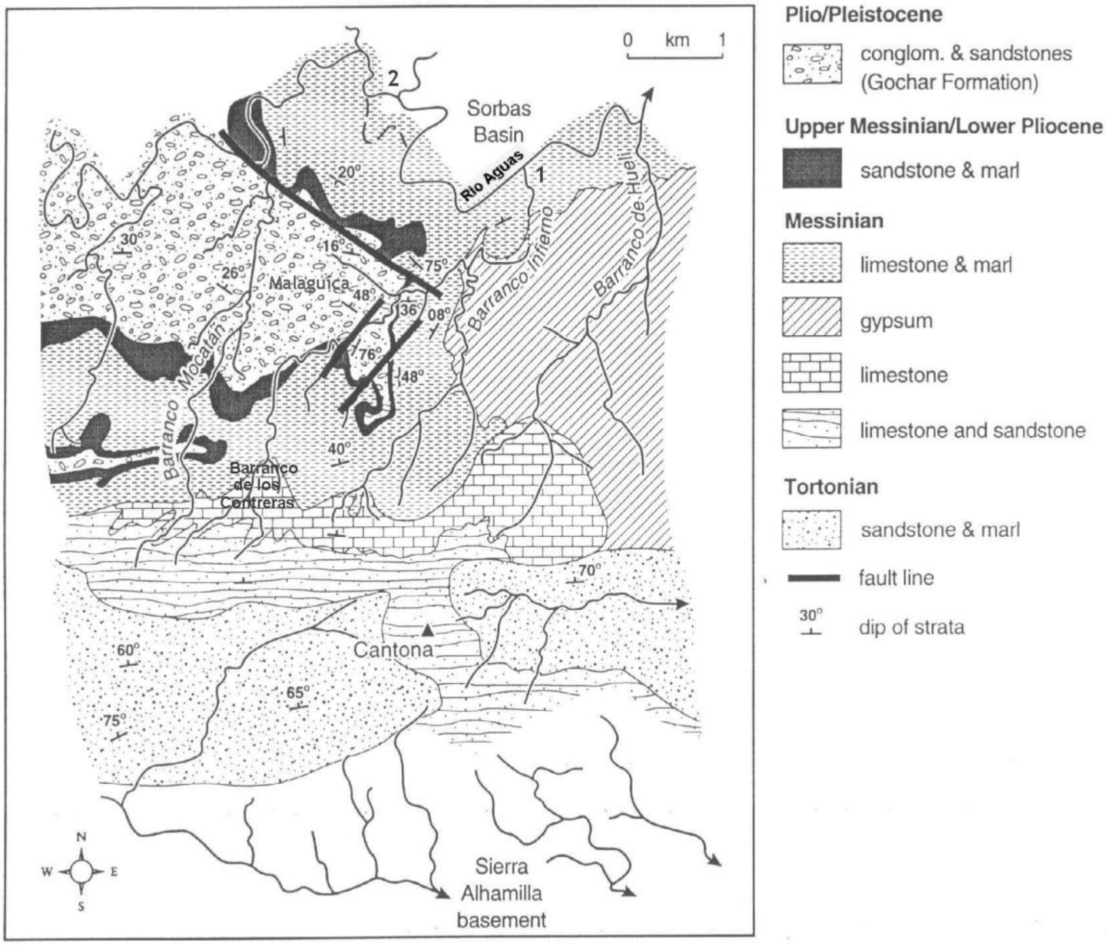


Figure 2.12 Geology and drainage in the study area (modified from Mather, 2000)

Changes in lithology are very obvious within the Barranco del Infierno channel. Bands of the Sorbas Member, which is white and chalky, form resistant waterfalls within the channel where it abuts Gochar material which is orange and silty. A change in channel form marks the contact between Sorbas Member material and gypsum which is easily identifiable by its crystalline nature. The Barranco del Infierno is associated with a cave system in the gypsum. This cave system consists of two main levels joined by a pitch of 30m, and is associated with one fossil gallery. The base level difference between the top and bottom of this cave system is approximately 40m (Mather, 2000). It is thought that the Barranco del Infierno and its tributaries eventually stabilised after the period of incision following the river capture. The lack of mature soil development and predominance of calcrete stones on the hillslopes and drainage divides of the catchment seems to indicate a loss of soil from the whole catchment at some point in the past. There is running water issuing from a spring in one part of the catchment at GR 577200 4104100 (Figure 2.13 at 1) in the Barranco de los Contreras and there is often standing water at the bottom of dry waterfalls in the Barranco. The cave system contains water year round. The highest point in the Barranco del Infierno study area is the hill La Cruz de San Marco (Figure 2.13 at 2) which reaches a height of 540m from the stream bed at 440m – a relative relief of 100m

Figure 2.13 Study area map (source: Mapa Topographica de Andalucía 1:10 000 1998). Numbers refer to points in the text of this chapter

The headwaters of the Barranco del Infierno in the Malaguica Hills contain fairly wide stream valleys with agricultural terraces, the majority of which are abandoned. It is the width of these valleys in the Gochar material which allows agriculture to be practised in this terrain. In the deeply incised stream channels which run through the carbonate and gypsum lithologies, agriculture is impossible due to the confines of the terrain. Most of the terraces contain at least one olive tree. These trees are generally large, and as olive trees can take up to 60 years to bear fruit under traditional *secano* agriculture techniques, it would seem to indicate that the terraces are not modern in origin. It is thought that much of the terracing in the Sorbas basin area reflects the 11th Century Moorish agricultural expansion (Sutton, 1999). Some of these abandoned terraces have been severely eroded with gullies of over 2m in depth running through them. Others have been piped underneath the terrace walls. The erosion is clearly subsequent to the terrace building. The erosion active in the terraced areas of the Barranco del Infierno indicates that the catchment had a period of some stability, but is now undergoing a period of localised destabilisation, possibly directly related to the terrace abandonment

2.5.3 Barranco del Mocatán

The Barranco del Mocatán joins the Rio Aguas approximately 13km above the river capture point at Los Molinos. The Barranco del Mocatán is also sourced, like the Barranco del Infierno's tributaries in the hills of the Cantona range which divide the Sorbas basin from the Rambla Lucainena drainage. Approximately half of the length of the Rambla from the confluence with the Aguas runs over Gochar material, occasionally cutting through to Cariatiz Formation material. The top end of the barranco runs over the Messinian limestone and marl of the Sorbas Member. The Barranco del Mocatán has fewer large tributaries than the Barranco del Infierno, and the drainage pattern on the meso-scale appears simpler than that of Barranco del Infierno. On the micro-scale however, the catchment is far more complex. The section of the Rambla that runs across Gochar material is extensively piped and gullied in a series of complicated badlands that rise approximately 40m from the channel bed. According to Mather (2000) the Barranco del Mocatán has a much steeper profile towards the headwaters than the Barranco del Infierno. At points along the profile of the Barranco del Mocatán, the underlying Cariatiz Formation is visible including white lacustrine bands. It often forms harder bands in the channel bottoms which occur as dry waterfalls. The junction of the Sorbas member and the Gochar Formation is also visible in the southern end of the study area . Again the Sorbas member forms more resistant bands in the Rambla bottom. Badland formations do not exist on this lithology as it is less erodible than the Gochar material. There are at least two areas of standing water in the Barranco del Mocatán within the study area. These are found at the base of the aforementioned dry waterfalls formed from outcrops of harder lithologies.

The middle of the study area section of the Barranco del Mocatán is dominated by a north-south orientated gravel capped escarpment in the weaker Gochar material (Figure 2.13 at 3) and a ridge Cerro de Juan Contreras (meaning ridge of Juan Contreras) acting as a drainage divide between Barranco del Infierno and Barranco del Mocatán (Figure 2.13 at 4). The highest point in the study area is a hill which rises to 534m from 470m in the Barranco de los Contreras and from 440m in the Barranco del Mocatán (Figure 2.13 at 5). It is possible that the col between the Cerro de Juan Contreras ridge and this hill could have been the site of one of the obsequent river captures that Mather (2000) describes. There is also a relict early Pleistocene landslide (Figure 2.12 at 6) that moved from the top of the drainage divide between the two catchments into the Mocatán catchment. This is an area of the catchment that has some of the most intense badland activity.

The Mocatán catchment contains many agricultural terraces which are probably of a similar age to the terracing in the Infierno catchment, most containing a solitary olive tree. Agricultural exploitation has been encouraged in the past by the wide valley floors of this catchment, and there is more terracing in the Mocatán catchment than in the Infierno catchment. Many of these terraces are unmaintained or abandoned and are cut through by deep gullies and pipes. Still more terraces have been isolated from the original channel that they were cut into by piping and stream capture, and left high and dry above the valley floor. Since 1994 however, there has been a resurgence of agricultural use of the west side of the Mocatán valley. The west side is less steep than the east side and has easier access for vehicles and people. Fields have been bulldozed out of hillsides, and old terraces flattened to make large fields for drip-fed olive and almond groves. In the east of the catchment where the majority of fieldwork for this thesis has taken place, there have been some attempts at new agricultural activity. Between April 1996 and September 1996 a road was cut down into the river valley across the northern flank of Cerro de Juan Contreras. This road truncated pediments and blocked gullies, and since its building has suffered very badly from piping and rilling, so much so that it is not really useable by vehicles. Some bulldozing of terraces at the end of this road has taken place, but certainly not on the scale of the agricultural development in the west.

2.5.4 Summary of geology and geomorphology of the study area

The study area's geology comprises Gochar sediment overlying and faulted against Cariatiz alluvial material and Sorbas carbonates. The majority of the field area is comprised of Gochar material. The geomorphology of the study area comprises areas of badlands in both catchments found in the Gochar sediment, with Mocatán having the larger of the two areas. Drainage divide rise up to 100m from the river channels. The top surfaces of drainage divides at about 510-540m comprise coarse gravel capped by a calcrete layer. Channels which are not of badland form on the Gochar formation generally have a wider profile and more gently sloping sides. Channels in lithologies other than those of the Gochar sediments generally form steep sided canyons. These canyons are found upstream of the badland area in the Mocatán catchment in the Sorbas member sediments and both above and below the badland area in the Barranco del Infierno in Sorbas member material and gypsum.

Abandoned agricultural terracing can be found in the Mocatán and Infierno catchments on Gochar material. Terraces are rarely found on Sorbas member sediments. Abandonment of these terraces has led to new incision in recent times. New agricultural activity in the Mocatán catchment is changing the shape of the catchment and may lead to more badland processes where landform has been disturbed. This is described in the humans, agriculture and landuse section of this chapter.

2.6 Vegetation in semi-arid areas

"Although the general lack of vegetation gives many dryland environments their distinctive character, few arid areas are devoid of vegetation of all types" (Bullard, 1997)

On a global scale, the limiting factors for photosynthesis and therefore plant growth are water and temperature (Leith and Whittaker, 1975). Along with this, the ratio of actual to potential evapotranspiration should be added as this correlates with plant net primary productivity (Thornes, 1985). In arid and semi-arid environments, plant production has an almost linear relationship with root zone soil moisture (Thornes, 1985). Therefore it is appropriate to say that aridity is the principal limiting factor of plant growth in deserts and semi-arid areas. Other factors that may limit plant growth include soil chemistry, soil erosion, soil organic matter and litter breakdown, but these really only become limiting factors when moisture-stress is reduced. Moisture becomes the limiting factor in plant growth below 600mm a^{-1} of rain (Bullard, 1997), The sporadic and intermittent nature of precipitation and the high temperatures in arid areas are not ideal for vegetation growth, and the irregular spatial and temporal distribution of precipitation is more significant in determining plant growth and positioning than actual amount of precipitation. Plants have developed various mechanisms to cope with these extremes of aridity, sporadic rainfall and temperature which make semi-arid and desert plant communities very distinctive in character (Bullard, 1997; Francis, 1994).

2.6.1 Adaptation of plants to cope with their environment

According to Evanari *et al* (1971) plants have developed a range of coping strategies which may be classified as physiological, morphological and behavioural to cope with the environments they are found in. Physiologic adaptation is change to the ways that plants function e.g. transpiration and photosynthesis. Morphologic adaptation is change to the plant structure, for example, change in leaf shape or size or stem height or thickness. Behavioural adaptation is a change in the ways that plants interact with the wider environment, e.g. their physical placement or interactions with other plants. Obviously, these developments and adaptations have taken place over long timescales and continue constantly. Plants evolve to fit the conditions they inhabit to improve their chances of survival. As the environment becomes, for example, more arid, plants will change to cope with the severity of the aridity and the adaptations will become more pronounced (Francis, 1994).

2.6.2 Plant responses to aridity

Francis (1994) has reviewed the literature concerning plants found in arid environments and a synopsis of this review can be found below in table 2.1. Plants can be divided into three types by their ability to live in environments dictated by moisture availability: hydrophytes adapted to live in waterlogged conditions, mesophytes living in humid conditions and xerophytes in arid conditions.

Mesophytes and xerophytes can both be found in semi-arid environments with xerophytes becoming more common and mesophytes less so as aridity increases.

Phreatophytes are mesophytic plants which cope with aridity by depending on groundwater. Phreatophytes are usually trees and shrubs with deep roots that reach the water table, and generally they use more water than other vegetation in the same environment as they have more access to water sources. The use of groundwater means that this vegetation is not rainfall dependant and so can survive long periods of drought as long as the water table stays within reach of the roots. Other mesophytic adaptations to drylands include plants with dense root networks which spread out near the ground surface to take advantage of any precipitation, dew or fog (Bullard, 1997).

The adaptations of xerophytes to arid environments take three different forms. Firstly, some plants are able to withstand desiccation, secondly, plants have developed that are active during the dry season and thirdly, plants have developed that are inactive during the dry season. Table 2.1 shows the physical characteristics of these three types and gives examples of plants that fall in these categories

Xerophytic adaptation	**Description of adaptation**	**Examples of plants using this adaptation**
Plants that withstand desiccation	Some lower plants can withstand prolonged desiccation and rehydration many times. They are metabolically inactive when dehydrated and resistant to extremes of temperature. During and after rain these plants become metabolically active and start photosynthesising again	Algae Lichens Mosses
Plants active during the dry season	Drought avoiding plants rely on adaptations to store water within tissue matter, metabolise more efficiently or reduction of transpiration losses. These adaptations can take the form of thick, dense cuticles, sunken stomata and hairy leaves which may be shed under extreme conditions to reduce the transpiring area. Large 'winter' leaves may be replaced with smaller drought resistant leaves for the dry period.	Cacti Succulents (e.g. *Sedum spp*) *Salsola spp*
Plants inactive during the dry season	Plants inactive during the dry season are those which store their energy in a rhizome or bulb, small perennial herbs and ephemeral plants. Plants with bulbs and rhizomes can lie dormant for a number of years until enough rain falls to encourage growth. Dwarf shrubs and perennial plants avoid drought by shedding leaves and stems during drought, and becoming photosynthetically inactive. Annual plants grow from seed, flower, set seed and die in the course of one year so all their growth is concentrated into the period after rain. Ephemerals are similar, but will often germinate after autumn rains as well as spring rains and live for a shorter time than annuals. Ephemerals often have special seed dispersion and germination mechanisms to improve success rates, and are generally shallow rooted. Up to 60% of plants in very arid regions are ephemerals. In less arid regions where the precipitation can support shrubs and other plants, this percentage will drop.	Monocotyledons such as orchids, lilies and narcissi Herbs and small perennial shrubs such as thyme, artemesia and lavender Annual and ephemeral plants such as wild pea (*Pisum sativum*) and poppies (*Papaver spp.*)

Table 2.1 Xerophytic plant types adapted from Francis (1994)

Another adaptation that plants in arid areas often have to make is to become salt-tolerant, or halophytic, as the surface of arid sediments often become salt-encrusted due to evaporation of water containing salts. Halophytes are able to live in conditions which non-salt tolerant plants would be unable to survive.

2.6.3 Vegetation and soil in semi-arid areas

Soils in arid and semi-arid areas are characterised by low levels of organic matter and nutrients, and high levels of soluble salts (Francis, 1994). Vegetation in semi-arid areas can cause chemical and mechanical weathering of bedrock and rock fragments. Microflora, lichens and root systems of higher plants all weather rock and encourage soil formation, but more importantly, the presence of plants on soils in semi-arid areas encourages the development of better soils. Various comparative studies of vegetated and non-vegetated areas have shown that there is strong spatial variation in the physical and chemical properties of soil in these areas (Francis, 1994) For example there is a correlation between crown size and increases in pH, total soluble salts and exchangeable sodium (Fireman and Hayward, 1952) and significantly higher values of exchangeable cations, organic carbon and nitrogen have been found under plants compared with non-vegetated areas (Romney *et al*, 1977; Rostagno *et al* 1991). Plant litter lowers the soil bulk density and increases infiltration rates which in turn makes the soil better for plant growth. For example Rostagno *et al* (1991) found that mean infiltration rates under shrubs were significantly higher than infiltration rates on bare ground (3.3cm hr^{-1} as compared to 0.5cm hr^{-1}). Litter is also the main contributor of nutrients and organic matter to soils (Francis, 1994, Bullard, 1997). Litter may be trapped around its plant of origin or redistributed by the wind to be deposited where it is caught by depressions, rocks or other plants According to Binet (1981) the sheltered, damp and protected environment directly underneath plants means that any litter trapped beneath will decompose more rapidly than that on a bare surface or trapped by something other than a plant. However the fertility of soils under vegetation declines rapidly with depth.

To summarise this process, there appears to be a positive feedback effect of the action of plants on soils in drylands. Plants encourage soil formation and improvement which in turn enables the soil to support more plants. This leads to a landscape where there are clumps of plants flourishing in these improved soil areas and surrounding areas of crusted or bare ground with little or no soil improvement. The differences between the vegetated and bare areas increase over time due to the self-reinforcing processes discussed above which leads to a landscape of reasonably low fertility containing hot-spots for succession or vegetation change (Puigdefábregas and Sanchez, 1996). This is discussed in the next section.

2.6.4 The spatial distribution of vegetation in semi-arid areas

The spatial variability of soils and vegetation in arid and semi-arid areas can often be considered a binary mosaic or two-phase mosaic known as groves and intergroves (Dunkerley and Brown, 1997). This mosaic gives the characteristic patchy appearance of the landscape in semi-arid areas with clumps or lines of vegetation surrounded by bare ground (see Plate 2.1).

This mosaic of crusted or bare ground patches and vegetated mounds or strips has frequently been interpreted as a response of vegetation to limited water supply (Puigdefábregas and Sanchez, 1996). The areas of bare soil usually have sealed surface crusts, some of which can be organic, for example cyanobacteria or lichen crusts, which makes them quite impermeable and they absorb little of the rain that falls on them. The runoff then moves downslope to infiltrate the vegetation hot-spot which will have greater permeability. It is quite possible for grove areas to receive almost twice the amount of moisture that would be expected for the climatological rainfall through runoff, which makes the intergrove areas much more arid (Dunkerley and Brown, 1997). This has been demonstrated by Tongway and Ludwig (1990) who used rainfall simulation in a binary mosaic landscape in eastern Australia. In the intergroves, runoff began after 7 minutes of rain at 29mm h^{-1}. In the groves, there was no runoff at all from the simulated rainfall.

Plate 2.1 Showing characteristic clumped vegetation on a hillslope

Puigdefábregas and Sanchez (1996) found a similar pattern in their study of the clump grass *Stipa tenacissima L.* in south-east Spain which found that lateral swales and bare ground patches produced more runoff and sediment yield than vegetated mounds of *Stipa.*. They also found that *Stipa* plants with low growth rates could be swamped by sediment carried onto their upslope sides forming crescent shaped tussocks or oblong tussocks with their long axis perpendicular to the slope. *Stipa* plants with high growth rates were able to maintain their circular shape by colonising the newly deposited sediment in an uphill direction.

It is interesting to note that in environments where plant populations have reached a level where resources have to be competed for, plants of the same species are usually regularly spaced which has been attributed to intraspecies competition for scarce resources , with the larger plant species being separated by greater distances than the smaller plant species. Plants of different species can be found growing together however, as, for example, shallow rooting species do not pose a threat to deep rooting species as they are competing for different resources (Bullard 1997).

It must be remembered that this pattern of grove and intergrove is not static, and changes occur over time. Vegetation patches build up biomass and degrade in cycles and they may change their size and shape through time (Puigdefábregas and Sanchez, 1996). Clumps that are extant in the landscape will accrete sediment either through overland flow deposition (as described above) or aeolian deposition. However the difference between the clumps and the bare ground can lead to differential erosion where the bare ground is eroded more easily than the vegetation patch (Bullard, 1997). This and other factors in erosional processes are discussed below.

2.6.5 Vegetation and sediment deposition and erosion

Soil erosion increases as vegetation cover declines, and the rate of increase is most rapid between 40 and 10% vegetation cover (Francis, 1994). The erosion of soil in dryland ecosystems is very destabilising because of the concentration of nutrients, organic matter and seeds in the top5-10cm of the soil. Therefore erosion rapidly reduces the fertility of the soil through nutrient loss, and the loss of infiltration and moisture retention capabilities of the soil (Francis, 1994). Lal (1976) estimated that a 10mm loss of soil would result in a 75% loss of soil productivity.

On unvegetated areas removal of sediment by splash or sheetwash produces erosion. Rain-splash can produce ponding and sealing of the ground surface which reduces infiltration and encourages overland flow which in turn strips soil, further lowering infiltration. Gully formation can be initiated under these conditions resulting in a positive feedback process which brings about bare slopes (Thornes, 1985). Vegetation significantly affects the distribution of water on hillsides through interception and also affects the erosive power of rainfall so that raindrops land on the surface at less than terminal velocity reducing their ability to detach sediment (Francis, 1994). Along with standing vegetation, litter plays an important role in reducing overland flow and increasing infiltration thus reducing the risk of erosion. The most severe erosion in semi-arid areas occurs during autumnal rains. At this time of year, the ground surface is at its most bare, with no protection from annuals or rhizome plants. This is the period when most sediment detachment by precipitation occurs (Francis, 1994). Surfaces that are able to support perennials or shrubs are more protected by the standing vegetation and the litter.

Lichens and algae are able to colonise dryland sediments that would be too inhospitable for higher order plants. This may have the effect of stabilising the slopes long enough for higher order plants to begin to colonise. Alexander *et al* (1994) have suggested a possible method for stabilisation. On sparsely covered slopes, lichens increase runoff but decrease sediment concentration in the overland flow by forming a biotic crust which protects the underlying sediment from erosion. When lichen cover is dense the decreased erosion allows an increase in the number of higher plants able to establish due to soil stability. These higher plants will eventually reduce runoff and increase infiltration rates. This demonstrates how a natural negative feedback mechanism can stabilise and recolonise what were bare slopes.

Clump vegetation acts as a roughness element in the landscape providing resistance to overland flow. This changes the sheetflow into channel flow between the clumps which in turn increases the erosive power of the water especially if turbulence occurs (Bullard, 1997). Work done in north-eastern Patagonia by Rostagno and del Valle (1988) identified groups of mounds with an average height of 41cm which is thought to represent a relict land surface where the channelling of runoff flow by vegetation clumps has caused differential erosion in the landscape.

Ephemeral and annual plants are less effective at creating their own micro-climates and protective clumps in dryland environments because of their temporary nature. Both ephemerals and annuals are very sensitive to rainfall and moisture and will develop over a period of 2-3 days for ephemeral and a few days for annuals after rain (Heathcote, 1983). It is quite possible for the amount of vegetation to increase dramatically after rainy periods in dryland areas. In a semi-arid area of Tanzania, the growth of annuals and ephemerals after rain can swell the vegetation cover from 3% to over 80% (Thomas, 1988). Because of the ephemeral nature of these plants, they are not in the environment when rain falls which means that they do not contribute to the ‘defence’ of the soil in the way that perennial and shrub vegetation does. Annual and ephemeral growth is often found on surfaces that show evidence of erosion and instability where more permanent growth of plants would be impossible.

Lazaro *et al* (2000) make the comment that spatial segregation of vegetation occurs in the Tabernas badland area due to spatial variation in areas of erosion and stability. All life forms appear to prefer the same, favourable environmental conditions. However, when favourable conditions do occur, shrubs become the dominant life form type . Annuals occupy an intermediate situation where there are some site stresses and lichens are displaced to dry and infertile but uneroded sites and between patches of denser vegetation and annuals. Extremely eroded areas have little if any vegetation cover. Lichens can survive extremely infertile conditions, but are as susceptible to erosion as higher plant species.

2.6.6 Vegetation and aspect

Aspect has been acknowledged as having an important role in controlling the distribution of plants and vegetation communities for almost 80 years as documented in a 1990 paper by Kirkby *et al.* One of the first studies to quantify the differences in vegetation cover that aspect can cause was by Shreve (1922) who identified differences in soil moisture and temperature on slopes with different aspect. Cottle (1932) found that soils on south-facing slopes in Texas were warmer than north facing slopes, had 5-15% lower moisture content and 24-44% greater evaporation rates. Boyko (1947) identified greater diversity of plant species on north facing slopes in Israel. Geiger (1973) identified that differences in vegetation with aspect could be found well into lower latitudes, and the reason for the differences of vegetation type between north and south facing slopes was attributed to the timing of maximum radiation. South-west facing slopes (in the northern hemisphere) have a maximum radiation occurring during the afternoon when soil moisture has already evaporated, whereas maximum radiation on north-east facing slopes occurs in the morning while there is still soil moisture available.

Dargie (1984) in a study of integrated interpretation of indirect site ordinations in south-east Spain concluded that temperature was the main determinant of plant species contrasts, and soil moisture was the most important determinant of vegetation cover and plant biomass. Dargie also found that the line of maximum contrast on hillslopes lies in a NE-SW axis. Kirkby *et al* (1990) identified the greatest aspect contrasts as being in the semi-arid mid-latitude regions where cloud cover is low. Kirkby *et al's* (1990) model of aspect induced assemblages of vegetation on hillslopes seems to support Dargie's conclusions that soil moisture differences are important in determining vegetation cover and biomass.

Lazaro *et al* (2000) found in the Tabernas badlands, south-east Spain that it was theoretically possible for lichen species to colonise stable southerly facing, infertile, fairly extreme environments. However, lichens were often unable to colonise these south facing slopes because of the erosional activity on south facing slopes which was higher than on slopes with other aspects.

In summary, aspect induces differences in the distribution of vegetation amount and type on hillslopes in semi-arid areas. Taking a northern hemisphere perspective, vegetation on south and south-west facing slopes is, in general, sparser with fewer plant species than that on north and north-east facing slopes. This in turn leaves south facing slopes more likely to be eroded than north facing slopes due to the sparseness of cover and therefore lack of protection from rainfall and overland flow. Larger, shrubby phreatophyte species are less likely to establish on south facing slopes as the water table is lower (Kirkby *et al,* 1990). The species that will establish themselves are likely to be the xerophytic plants that can cope with the higher temperatures and increased moisture stress.

2.7 Vegetation in Almería.

Whilst most of the area of Spain bordering the Mediterranean Sea has very typical Mediterranean plant assemblages, Almería is different. Because of the atypically dry climate, the plants species found in Almería consist of some hardy, drought tolerant, Mediterranean species, some plant species from northern Africa and some species found only in this area (Sole-Benet and Alexander, 1996). This unusual assemblage of plants can be attributed to moisture stress due to the unusually low rainfall in this area of Spain. Along the southern coast of Spain to the west of the Sierra Nevada, annual rainfall totals are 907mm in Gibraltar and 469mm in Malaga. In contrast Almería City receives on average 221mm, Garrucha 211mm and the Cabo de Gata, just 130mm (Tout, 1987). As discussed in section 2.2 of this chapter, the climate classification this area of south-east Spain determines the region as semi-arid to arid in climate as opposed to Mediterranean which is the classification for Malaga and Gibraltar.

The variety of plant species can be partly attributed to south-east Spain's position close to Africa and within Europe therefore allowing plant species from both Africa and Europe to establish themselves. It can also be attributed to the fact that this area was not glaciated during the previous ice-age and acted as a refugia for many plant species allowing them to survive the ice-age (Roberts, 1992). However, according to Montero and Gonzalez Reboller (1983) the area is unable to support tree-like vegetation due to its bioclimate, other than in some of the mountainous areas where there is higher precipitation, for example the northern side of the Sierra de los Filabres where the annual precipitation in 440mm a year (Capel Molina, 1990).

2.7.1 Natural or plagioclimax vegetation communities?

One of the commonly seen vegetation communities in Almería is the shrubland or *Matorral* community. This is found on hillsides throughout the area and consists of a formation of woody plants whose aerial parts are not differentiated into trunk and leaves because they are ramified from the base and of a shrubby habit. The majority of the *Matorral* found in this part of Spain would be considered low to middle *Matorral* as defined by Tomaselli (1981), with cover height between 0-2m. Cover by *Matorral* (R) is distinguished as dense ($R>75\%$), discontinuous ($50\%<R<75\%$) or scattered ($25\%<R<50\%$) and scattered to dense *Matorral* cover can be found throughout the area, although true dense *Matorral* is not common. Tomaselli describes low discontinuous *Matorral* as being part of the last stage of degradation of more complex formations, and comments that this type of cover is frequent in Spain. Low scattered *Matorral* is found in areas that are subjected to intensive grazing which hinders the growth of the vegetation and keeps many shrubs in a dwarf state. It would seem that the *Matorral* vegetation in Almería is at the limits of its range partly due to water stress and partly due to grazing and human induced changes to the landscape. In the Cabo de Gata in the extreme south-east of Almería, *Matorral* disappears almost completely to be replaced with salt steppe flora due to the aridity of the area (Tout, 1987). There are many species found in *Matorral* cover in Almería, and there are different *Matorral* communities to be found at different aspects and altitudes. Species composition of *Matorral* will therefore only be described in detail at the field site level of analysis.

Another plant community commonly found in Almería is that consisting of *Stipa tenacissima*, or esparto grass and related plants. *Stipa* can be found on stony hillsides and forms a large tussock, often more than a metre in diameter. Mature *Stipa* tussocks often show a ring structure with four zones, the growth zone, the maturing zone, the senescent zone and the dead litter zone (Puigdefábregas and Sanchez, 1996). *Stipa* tussocks produce feathery seed heads most years, but according to Puigdefábregas and Sanchez (1996), seed reproduction is rare in semi-arid areas and the tussocks spread by means of vegetative layering from the growing zone. *Stipa* tussocks are an example of patchiness in semi-arid areas (as described in section 2.4) where the tussocks receive runoff from the slope above and become islands of growth in an otherwise sparsely vegetated area. Other plants can be associated with areas of *Stipa* however, including shrubby plants such as gorse (*Ulex spp.*) and, during moister periods of the year, annuals. *Stipa* tussocks are fairly ubiquitous throughout Almería and can often be found within *Matorral* communities. Sole-Benet and Alexander (1996) indicate that *Stipa* in the El Cautivo field area is found on stable ground, and indeed through observation in the field it has been noted that *Stipa* is not often found in areas that are obviously suffering from erosion. This may be to do with the reproductive method of *Stipa* in semi-arid areas. If an old tussock is needed to vegetatively start a new plant, then continuity of presence of *Stipa* tussocks will be needed, and it is hypothesised that this stability will not be provided in a geomorphologically unstable environment because of the erosion of the soil.

Ruderal vegetation, or vegetation that is found on disturbed land is characteristic of many areas in Almería. This disturbed land includes agricultural terraces that have been left fallow or abandoned, areas such as badlands that have seen active erosion in the recent past and other places where earth/sediment has been moved and then left alone either by human or natural forces. The types of plants that can be found in these areas are annuals and ephemerals during periods with more moisture (i.e. after rain), single-stem grasses and, over a longer period, perennial herbs and dwarf shrubs which may eventually start to form a *Matorral* community if not disturbed again. The areas where ruderal vegetation is found are those that are most prone to sediment-removal during periods of low vegetation cover such as autumn and winter and therefore the areas most at risk from erosion.

Another naturally occurring plant community found in Almería is that of lichens mosses and organic crusts, a general term for a bacterial or algal microphytic crust which can often be found on the surface of otherwise unvegetated areas and also in the gaps between shrubs in sparsely vegetated areas and as indicated in section 2.4.5 of this chapter have some part to play in soil surface stabilisation by reducing surface sediment erosion (Alexander and Calvo, 1990; Alexander *et al*, 1994; Lazaro *et al*, 2000) .

2.7.2 Introduced species

Almería has some very conspicuous introduced species of plants. These are mainly plants that have been imported from other arid areas of the world which have found a niche in the Almerían ecosystem and flourished. One of the most distinctive introductions is the prickly pear (*Opuntia ficus-indica*) which is a Central American cactus introduced partly as a food crop and partly as stock control hedging where its long spines are very useful. Another three introductions are the succulent plants sisal (*Agave sisalana*), aloe (*Aloe* spp.) and the century plant (*Agave americana*). In the past sisal was experimentally cultivated to make rope and there are still large fields of sisal plants to be found in parts of Almería. Aloe is less obvious in the landscape, but was brought to Almería from Central America for its use as a general healing agent and can be found in gardens and around abandoned settlements.

Eucalyptus (*Eucalyptus spp.*) trees are a common sight along Almería's road network where they have been planted for shade purposes. This Australian tree grows well in the dry environment due to their deep roots which can reach deep reserves of groundwater, unlike most European trees which are unable to survive in the Almerían environment without irrigation or river channel moisture

2.7.3 Cultivated species

The most obvious cultivated species in the Almerían landscape, outside of the greenhouse agriculture, are the olive (*Olea europa*) and the almond tree (*Prunus dulcis*). These are indicators of *secano* or dry-farming which is a farming technique that does not use irrigation (Tout, 1990). Olive trees can be found on almost every terrace in Almería where they were planted for the harvest of olives and oil. Olive trees are often an indicator of terraces which are now abandoned and unrecognisable as such. European Community grants have enabled farmers to plant olive trees in large fields where they are drip fed through pipes so that they grow faster and produce a larger crop (Thornes, 1995). Almond groves are less common than olives in this area, but individual trees can be found on terraces and around human habitation. Self-seeded almond and olive trees can be found in areas with dense *Matorral* cover. Other non-irrigated cultivated species to be found in Almería are citrus trees and cereal crops. The *regadio* farming technique which uses irrigation produces a huge range of fruit and vegetable crops, much of them under *los plasticos* where large plastic greenhouses are used to raise various vegetables year round for export (Tout, 1990; Wilvert, 1993). As these crops could not survive without irrigation, they are not generally found outside of their protected environments.

2.8 Vegetation in the field area

Within the two study catchments three main types of plant communities can be found. Approximately 40% of the field area is vegetated with some sort of *Matorral* or degraded *Matorral* community, approximately 20% is covered in *Stipa* grassland community and the other 40% consists of either bare ground (cultivated or eroded) or areas of ruderal plant communities. Cover descriptions and lists of dominant species types in each community are set out below, and a full listing of plant species identified in the field area can be found in Appendix 1

2.8.1 *Matorral* type communities

The *Matorral* communities in the field area consist of *Anthyllis-Salsola-Thymelea* dominated vegetation in the *Mocatán* catchment and *Anthyllis-Cistus-Thymelea* dominated vegetation in the Infierno catchment with other shrub vegetation to be found associated with these communities. A species list of all shrubs identified in the field area can be found in Table 2.2. Other plant species are also found in the shrubby cover including many different species of annuals, perennials and grasses. In the Mocatán catchment, the *Matorral* community is usually to be found on ridges between channels and above catchment headwaters. It is rarely found in channels or on the lower slopes. In the Infierno catchment the pattern is slightly different and the *Matorral* community can be found on some, but not all ridges, also on abandoned terraces within channels of the Infierno in the Malaguica area where it has become well established.

2.8.2 *Stipa* communities

Stipa tenacissima is often associated with a stony surface and small bushes of *Anthyllis*, *Cistus* or *Helianthumum* and *Thymus* species. Often species of lily or iris are found in these communities as well. *Stipa* communities can be found on the top of ridges in both the *Mocatán* and Infierno catchments. This community is particularly associated with the gravel cap that runs along the watershed between the two catchments, the top of the ridge of Cerro de Juan Contreras, the Sorbas material hills to the south of the field area, and the hogs-backs that run into the Malaguica area of the Infierno catchment (see map in Figure 2.13).

Individual *Stipa* tussocks can be found in many places in the field area, but the *Stipa* community as described appears to prefer the hilltops. The Queens University Field Guide to the Sorbas basin (1991) argues that a *Stipa* community indicates an extremely degraded environment following land abandonment. However, the positioning of the *Stipa* communities both in the field area and as observed outside of the field area seems to indicate that this community can flourish in an environment that cannot support a proper *Matorral* community because it is too dry (i.e. it is at the top of the watershed with no runoff fed onto it). As commented above, *Stipa* establishes itself best in a stable environment, and it would seem that these *Stipa* rich communities have become established on some of the drier, but stable hillslopes in the field area.

Anabasis articulata	*Phagnalon spp*
Anthyllis cytisoides	*Phlomis lychnitis*
Anthyllis terniflora	*Phlomis purpurea*
Artemisia spp.	*Pistacia lentiscus*
Asparagus stipularis	*Polygala rupestris*
Cistus albidus	*Prunus dulcis*
Cistus lavendufolium	*Pulicaria odora*
Cistus libanotis	*Rhamnus lycioides*
Crassula spp	*Rosmarinus officinalis*
Daphne gnidium	*Salsola spp. a*
Dorycnium pentaphyllum	*Salsola genistoides*
Frankenia thymefolia	*Salsola spp. like glasswort*
Fumana ericoides	*Sedum sediforme*
Helianthemum almeriense	*Sideritis spp. a*
Helianthemum apenninum	*Sideritis spp. b*
Helianthemum lavendulifolium	*Thymelea hirsuta*
Launea spinosa	*Thymus capitatus (variegated)*
Launea spinosa	*Thymus capriatus*
Limonium insigne	*Thymus longiflora*
Nerium oleander	*Thymus vulgaris*
Olea europaea	*Ulex parviflora*

* Note : some species reported at genus level due to uncertainty in identification.

Table 2.2 List of shrub species to be found in the field area.

2.8.3 Vegetation on degraded or disturbed land

The vegetation communities found on degraded or disturbed land in both the Mocatán and Infierno catchments are quite variable, but almost all degraded/disturbed areas are characterised by having fewer shrubs and more annuals and soft grasses than other areas. The channel bottoms in the *Mocatán* catchment are a good example of disturbed land, and the type of plants that can be found here include false esparto grass (*Lygeum spartum*), which seems to be an indicator of disturbance as it appears only to be found in areas which have been disturbed. Other plants to be found in disturbed areas include *Salsola spp.* which is a hardy bush that is found throughout both catchments and seems able to survive erosion, and small halophytes such as *Limonium insigne* and sea holly (*Eryngium spp.*).

In the spring, after rainfall, formerly bare areas become covered in ephemeral and annual plants, including numbers of leguminosae, compositae and umbelliferae as well as soft grasses like *Hordeum spp*. and *Agrostis spp*. which give these formerly bare areas a lush vegetated appearance. As discussed in section 2.4 these plants germinate after rain, so they offer little protection from sediment detachment by overland flow. Visual inspection indicates that these areas suffer the most from surface erosion and are frequently rilled, piped and gullied to a greater extent than under other plant communities within the catchments.

2.9 Humans, landuse and agriculture in south-east Spain

2.9.1 Human impact on the environment in south-east Spain – a brief history

Pollen records from a variety of sites in the western Mediterranean suggest that there was a period of mesic climatic conditions between 12000 and 6000BP when subhumid woodland species advanced from their glacial refugia. The record then shows that arid conditions became established fairly rapidly in this area after 6000BP (Allen, 2001). A pollen record for Padul near Granada shows a decline in tree pollen after 6360±85 BP. Gilman and Thornes (1985) attribute this decline in tree cover to human intervention but it has been established by Roberts (1992) that changes in flora from subhumid forest to sclerophyllous evergreen communities were not necessarily brought about by human activity as sclerophyllous shrubland is extant in the pollen records of both California and southern Australia before the introduction of agriculture into these areas. The decline in forest cover could therefore be attributable to a combination of environmental factors including both human intervention and climate change. However it is undoubted that the rise in agro-pasturalism in the Neolithic period and the decline in Mesolithic hunter-gatherer groups would have had a great impact on the environment. Trees and scrub have to be cleared to make fields for agriculture (Allen, 2001). Montero and Gonzalez Reboller (1983) do not think the extreme south-east of Spain has ever been able to support woodland vegetation in any great amount because of its bioclimate, and the climax vegetation would have been more or less open shrubland.

2.9.1.1 Prehistory in SE Spain

Work by Gilman and Thornes (1985) on the land use and prehistory of south-east Spain makes it quite clear that there are a surprising number of archaeological sites from the Neolithic to the Bronze age (approximately 7000-1200 BP) in this arid region; surprising because of the problems that aridity brings to agriculture which meant that these peoples were using some types of irrigation techniques. The investigations by Gilman and Thornes (1985) also demonstrate that the territory surrounding the archaeological sites investigated in the Vera basin (see Figure 2.6 for position of the Vera basin) has suffered little erosion since the abandonment of the settlements. This is also surprising considering the appearance of the terrain around the site which includes badlands and incised slopes. Gilman and Thornes (1985) set out to discover what percentage of the land surrounding the settlements up to a 2 hour walking distance was under certain land-use types, including whether it was possible that the land could have been irrigated, which depends on the number and discharge of springs. The conclusions were that Neolithic and Copper Age settlements in the driest parts of SE Spain were positioned to optimise the use of water for irrigated (*regadio*) agriculture. However it was discovered that Bronze Age settlements were generally sited in more defensive positions which did not necessarily optimise the potential for irrigation. This points to a socio-economic change during this era which meant that defence became more important. Gilman and Thornes (1985) point to growing competition over increasing investments in the land (in the form of labour on terraces and other irrigation techniques for example) that actually necessitated the need to protect these investments by moving to more defensible situations.

From the work done by Gilman and Thornes (1985) it can be extrapolated that the land in Almería has been used by humans for arable and grazing purposes for over 6000 years. It is thought that the human occupation of the arid lowlands of south east Spain was only able to happen because of the development of hydraulic technology during the Copper and Bronze Ages and it is clear that the importance of these new irrigation techniques formed part of a pattern of agricultural intensification in the area. Without irrigation techniques, there could have been no farming carried out in the lowlands of the arid south east of Spain.

2.9.1.2 Early history

The flourishing agriculture and metalworking of south-east Spain attracted the Phoenicans from North Africa in around 1100BC who engaged in trade with the peoples of south east Spain and settled in the area. The Greeks arrived at around 600BC and brought with them olives and vines which soon became an established part of agriculture in south east Spain. Greek trading settlements were established on the coast (Queens University Belfast, 1999). The first indigenous Spanish Kingdom, Tartessus arose in conjunction with the Greek and Phoenician colonisers. This kingdom was known for its advanced metalworking and agricultural practises, the latter introducing new methods of farming to the south of Spain (Camelot International, 2001). This Kingdom was overthrown in around 500BC with the rise of Carthaginian power in the Iberian peninsula. The Carthaginians also brought with them improved farming practices and other economic processes such as mining and fishing. The Romans who were at war with the Carthaginians, brought an end to this economic improvement and spent two centuries subduing the peoples of the Iberian peninsula. The conquest of the Iberian peninsula was completed in AD19 and south-east Spain became part of Baetica. The province of Baetica exported wheat, wine, metal, olive oil, cloth and manufactured goods to the rest of the Roman Empire. The Romans established new towns and improved communications between them. Aqueducts were built to improve water distribution, and an result of this was that irrigation techniques were improved and could reach a larger amount of what had originally been *secano* agricultural areas. Remains of Roman aqueducts and canal networks are to be found in Almería province, some of this engineering perhaps dating even further back to Bronze Age irrigation systems (Camelot International, 2001). The Romans are also known to have built terraces in North Africa where their remains have been found. Use of this technique is likely to be applicable to their occupation of Spain as well (Queens University Belfast, 1999).

2.9.1.3 The dark ages and the arrival of the Moors

After the Roman administration left Spain in the early 400s AD the Vandals moved into northern Spain and then southwards into southern Spain, and they were succeeded by the Visigoths who by 475 AD controlled almost all of the Iberian peninsula (Camelot International, 2001). The gothic kingdoms of Spain endured until 711 AD when the Moors crossed into Andalucía from North Africa. They had succeeded in conquering most of Spain by 718 AD, and named the area of the peninsula under their control as Al-Andalus. The Moors brought with them technology and science that has shaped the landscape, language and culture of Spain (especially the south of the country) up to the present day. In Andalucía the Moors introduced new crops such as oranges, almonds and sugar cane. However there is a lack of documentary evidence that the Moors invented the irrigation techniques found in Spain (Queens University Belfast, 1999). One interpretation is that the Moors found established irrigation systems, perhaps of Roman or earlier origin, and improved on them. The Moors are also known to have diffused and synthesised technology from Near Eastern societies; for example the technique of the *qanat* or horizontal well appears to be of Persian origin and has been dated back more than 2000 years (Sutton, 1999). A water harvesting system known as an *aljibe* is also thought to have been introduced to Spain by the Moors during their occupation (Van Wesemael *et al*, 1998). Whether the Moors invented, improved or brought the technology with them, the crops that they introduced into Spain needed to be irrigated for example oranges, carobs, dates and cotton – none of these crops can grow in semi-arid south east Spain without irrigation. The Moors changed the agricultural landscape of south east Spain and have left their mark in ways which have endured until the present day. For example in 960AD the *Tribunal de las Aguas de la Vega de Valencia* was created to regulate water distribution. This committee still meets weekly, emphasising how important water rights and irrigation still are in Spain (Queens University Belfast, 1999).

2.9.1.4 After the Moors

The *Reconquista* of Moorish south east Spain by the Christian forces of Queen Isabella of Castille and King Ferdinand of Aragon which ended in 1492 put an end to the last Moorish state in Spain. The Moors were allowed to continue to live in Spain and practise Islam, but continued unrest between Moslems and Christians eventually created a situation where Moors were instructed to convert to Christianity or leave the country. The converted Moslems, known as Moriscos were finally driven out of Spain due to civil unrest between 1609 and 1614 by Phillip III. When the Moors left, they took their agricultural expertise with them (Queens University Belfast, 1999). The loss of the Moorish agricultural methods and efficiency led to a decline in productivity of the land as irrigation systems broke down through neglect. McNeil (1992) has identified a period of soil erosion in Alpujarra area caused by neglect of terraces after the *Reconquista*. The expulsion of the Moors led to the land being settled by people unfamiliar with the terracing and irrigation methods of the Moors and the consequence of the change in land management was erosion of the neglected terraces. This sort of breakdown in the agricultural functioning of the countryside was exacerbated by the redistribution of land to a small land-owning class with the majority of the population involved in agriculture as landless labourers (Queens University Belfast, 1999). In 1845, Richard Harris's 'Handbook for travellers in Spain' described large tracts of the Andalucían countryside as a depopulated wasteland (Tout 1990). Agricultural reform was attempted between 1931 and 1936 during the Second Republic. The attempt was to bring social justice to a semi-feudal state. However the Civil War between 1936 and 1939 left Spain in much the same state agriculturally that it had been in since the end of the Moorish influence in 1614. Almería was known as the 'forgotten province' and was a byword for backwardness and underdevelopment (Tout, 1990). In the 1960s the Campo de Níjar to the south of the Sierra Alhamilla was described by Garcia Lorca (1977) as the most depressed area in Almería which was then the most depressed province in Spain. The main means of livelihood in this area was the collection of esparto grass (*Stipa tenacissima*). Schemes such as the planting of sisal as a cash crop were undertaken experimentally, but with little success (Tout, 1990).

2.9.1.5 The latter half of the 20th Century.

Until 1954 agriculture in Almería province was mainly subsistence, i.e. crops were grown to support families on holdings, rather than for cash, and yields were low. After 1954 a gradual change in agricultural techniques occurred on the plains of Almería; this being the introduction of sand-plot agriculture (Tout, 1990). This agricultural technique, combined with the introduction of plastic greenhouses (*los plasticos*) onto the southern coastal plains of Almería has revolutionised farming in this part of the province. With irrigation, these greenhouses raise vast quantities of salad crops for the winter and early spring markets of Europe without the costs of heating the greenhouses, unlike further north in Europe. However with the intensive use of the land and irrigation of the crops come the problems of salinisation and groundwater drawdown. In 1990 more than 100 Hm^3 of groundwater were extracted and only 43 Hm^3 recharge occurred. The aquifers are becoming exhausted and more saline due to the heavy use of groundwater by these agricultural practises (Tout, 1990). There are also problems with overuse of pesticides, residues of which are found on the vegetables exported. The high pesticide use also has an effect on the health of the people who work in these greenhouses (Tout, 1990). In 1990 only 30% of Almería was cultivated, and 70% of that was under dry-farming (*secano*) techniques. The remaining 30% of *regadio* or irrigated agriculture produced 80% of the agricultural income of the province. 34% of the population of Almería was engaged in agriculture as a living (Tout, 1990).

In the Sorbas basin there is some evidence of attempts at sand-plot agriculture. There are several abandoned greenhouses along the main road (the N-340) which runs through the basin. However from observation it appears that subsistence agriculture has continued in the area. This means that the agricultural landscape in the Sorbas basin until recently consisted mainly of small terraces, many with a single olive tree. Smallholdings are still common in this area, and these can be seen to be growing a number of crops for home consumption, for example peppers, beans, tomatoes. In the wetter areas, for example in the bed of the Rio Aguas near Sorbas there are citrus trees and other crops that need more water. However, there has been a revolution in the land use in the Sorbas basin in the last 5 years, which is related to Spain's accession to the European Union (EU) in 1986 and is described below.

2.9.1.6 Accession to the European Union

Spain became a member of the then EEC in 1986. The membership of the EU has brought with it many benefits for Spain, especially for its poorest southern provinces Almería, Murcia, and Granada (Barth, 1995). Almería is considered a less favoured area by the EU and so is eligible for extra funding and grants. On the macro-scale these grants have come in the form of part-finance for the Autovia del Mediteranée which was built in the early 1990s. The motorway has provided much better communication with the rest of Spain, and so the rest of Europe than it enjoyed previously, opening up more markets for the produce grown in *los plasticos*. This has led to an intensification of farming in the *plastico* areas. However, other grants have been made available to farmers to plant olive and almond trees and farm these as cash crops as opposed to a subsistence crop as in the past (Wilvert, 1993). To make the olive and almond orchards productive in as short a time as possible drip-fed irrigation is used. This has reduced the time period for reaching maturity and therefore fruiting in olive trees from approximately 60 years to less than 10 (Walsh, pers comm). The new plantations of olives and almonds have entailed the construction of large 'pseudo-terraces' (Grove and Rackham, 1998). Barth (1995) has identified four major changes that have come about due to Spain joining the EU. These are:

Grading and levelling of the traditionally terraced crop land in order to mechanise farms.
Abandonment of fields of low productivity or inaccessibility by mechanised equipment.
Introduction of new crops like sunflowers and extensive arboriculture by changing the conventional fallow system.
Intensification of cropping systems by the introduction of irrigation methods.

The Sorbas basin agricultural landscape is currently undergoing three of the four changes mentioned above. Terraces are being levelled to make much larger fields and these fields are being planted with drip-fed cash crops of olive and almond trees. New abandonment of the small 'old-fashioned' terraces appears to be happening in some areas of the Sorbas Basin, although many parts of the Basin have terraces that have apparently been abandoned for many years. The importance of terraces in the landscape as a method of preventing erosion is discussed in the following section.

Naveh (1995) comments that the shift from diversified local agriculture to large-scale agro-industrial farming funded by the E.U. means that high-tech and high-input agricultural practises will lead to an increase in the rates of air, water and soil pollution, soil erosion, salination and siltation. The soils of arable slopes which are cultivated by heavy machinery are losing their fertility and there is a loss of flora and fauna due to the change in agricultural practise.

2.9.2 Terraces – a very important part of the semi-arid landscape

Terracing as mentioned above has been part of the landscape of south east Spain for almost as long as agriculture has been practised here. Allen (2001) comments that terracing is a legacy of the domestication and cultivation of wheat and other grains. Crude terraces were in place by the Copper Age (Gilman and Thornes, 1985) and terracing techniques were refined by the Phoenician, Carthaginian, Roman and Moorish occupation of south east Spain (Queens University Belfast, 1999, Camelot International, 2001). A high percentage of the landscape in south east Spain is currently terraced or appears to have been terraced in the past. However it can be deduced from observation that many of the terraces that can be seen in the landscape are abandoned, especially in areas difficult to reach for example, on high mountainsides. This has to do with the decline of population in the countryside due to on-going rural-urban migration and take-up of jobs in the coastal tourist industries (University of Manchester, 1993; Thompson and Scoging, 1995). An economic report by La Caixa (2000), a Spanish Bank stated that there has been a loss of 300 000 agricultural jobs in Andalucía in the past 20 years (La Caixa Bank, 2000) which will have obvious implications for the management and maintenance of terraces.

2.9.2.1 Anatomy of a traditional terrace

Most of the terraces observed in the field are bench type terraces which consist of an upslope wall and a downslope wall with a graded surface between them which has a slight depression behind the downslope wall (see Figure 2.14). Water therefore drains downwards across the surface of the terrace, and is then directed into a flood diversion channel at one side of the terrace which drains onto the next terrace. When terraces are properly maintained, the soil that has accumulated behind the downslope riser is ploughed back up the terrace in a regrading operation. The terrace walls are maintained with stone wall facing, and any sediment accumulation from side slope rills or gullies is removed. Generally terrace maintenance has the effect of increasing infiltration and reducing runoff (Thompson and Scoging, 1995)

2.9.2.2 Terrace degradation

The result of terrace abandonment is ultimately loss of fertile soil through erosion as when terraces are no longer maintained, they begin to fall apart. Preferential erosion takes place within the disturbed ground of abandoned terraces and the stages of degradation include erosion by pipes, rills and gullies. Thompson and Scoging (1995) have studied terrace degradation at Turré in the Vera basin, about 20km downstream of Sorbas on the Rio Aguas. Their field observations concluded that pipes and gullies can occur in terraces within two to three years of abandonment. There are several stages of erosion of terraces starting with rilling and small scale piping followed by gullying, some of which may be caused by pipe collapse and then finally integration of the entire terrace erosional system with the valley drainage. Terraces are most vulnerable to erosion in the medium term when abandoned, and in the short term during fallow periods where vegetation cover is scanty or after grazing

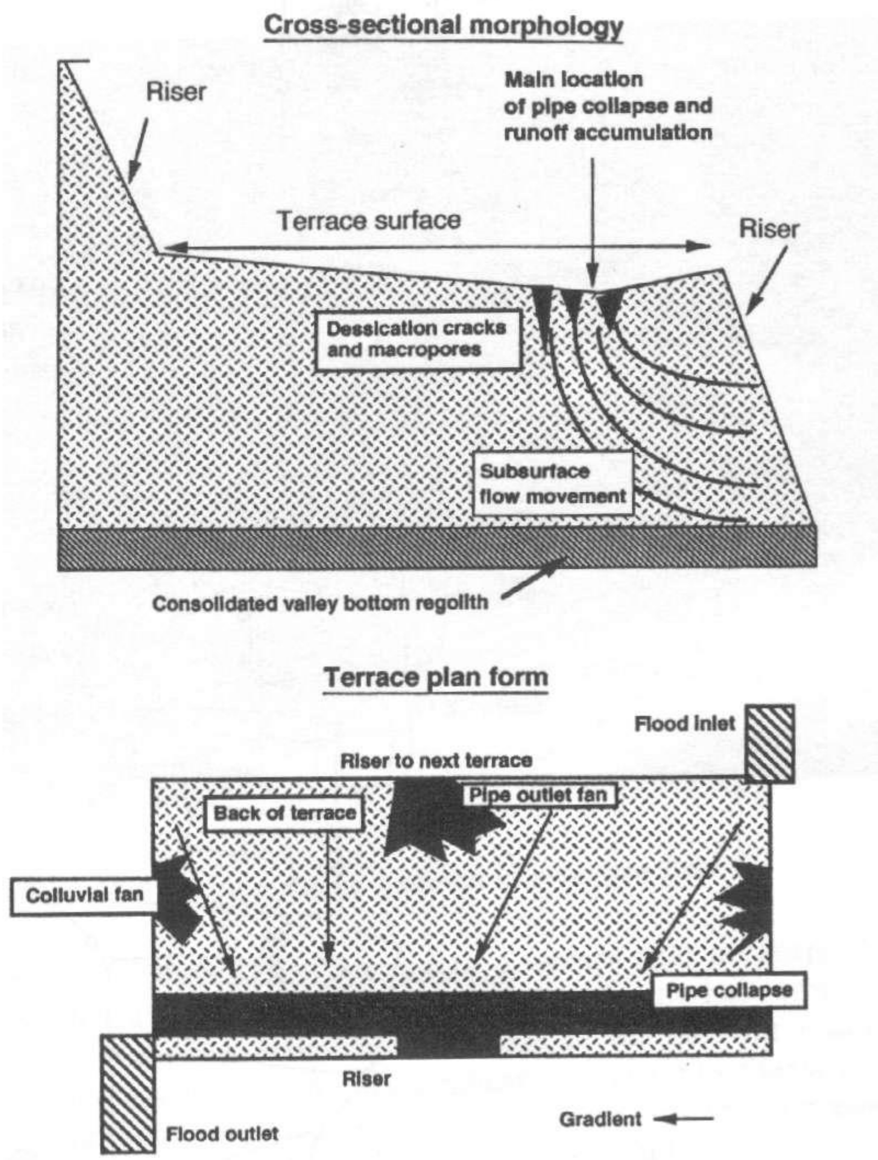


Figure 2.14 Cross section of a terrace (from Thompson and Scoging, 1995)

Thompson and Scoging's (1995) stages of terrace erosion are shown in Figure 2.15 and are explained below:

Decline or cessation of management leads to localised surface erosion. Failure to plough and regrade leads to surface crusting and accumulation of water behind the downslope terrace wall. Wetting and drying leads to desiccation cracking behind the riser.

Rill and sheetwash erosion acting on the valley sides brings material onto the terrace surface which distorts the terrace surface, channelling water to the centre of the terrace. Desiccation cracks are formed in the crusted material which can act as macropores during the next rainfall event. The runoff enters the terrace material and becomes available for pipe formation.

Failure to maintain terrace walls results in occasional collapses during rainfall which has been associated with groundwater seepage and pipe development. Pipes develop due to exploitation of macropores, tree root paths and along the line of separation between terrace material and the underlying valley regolith. If the soil is sodic, dispersion of the material also contributes to pipe formation.

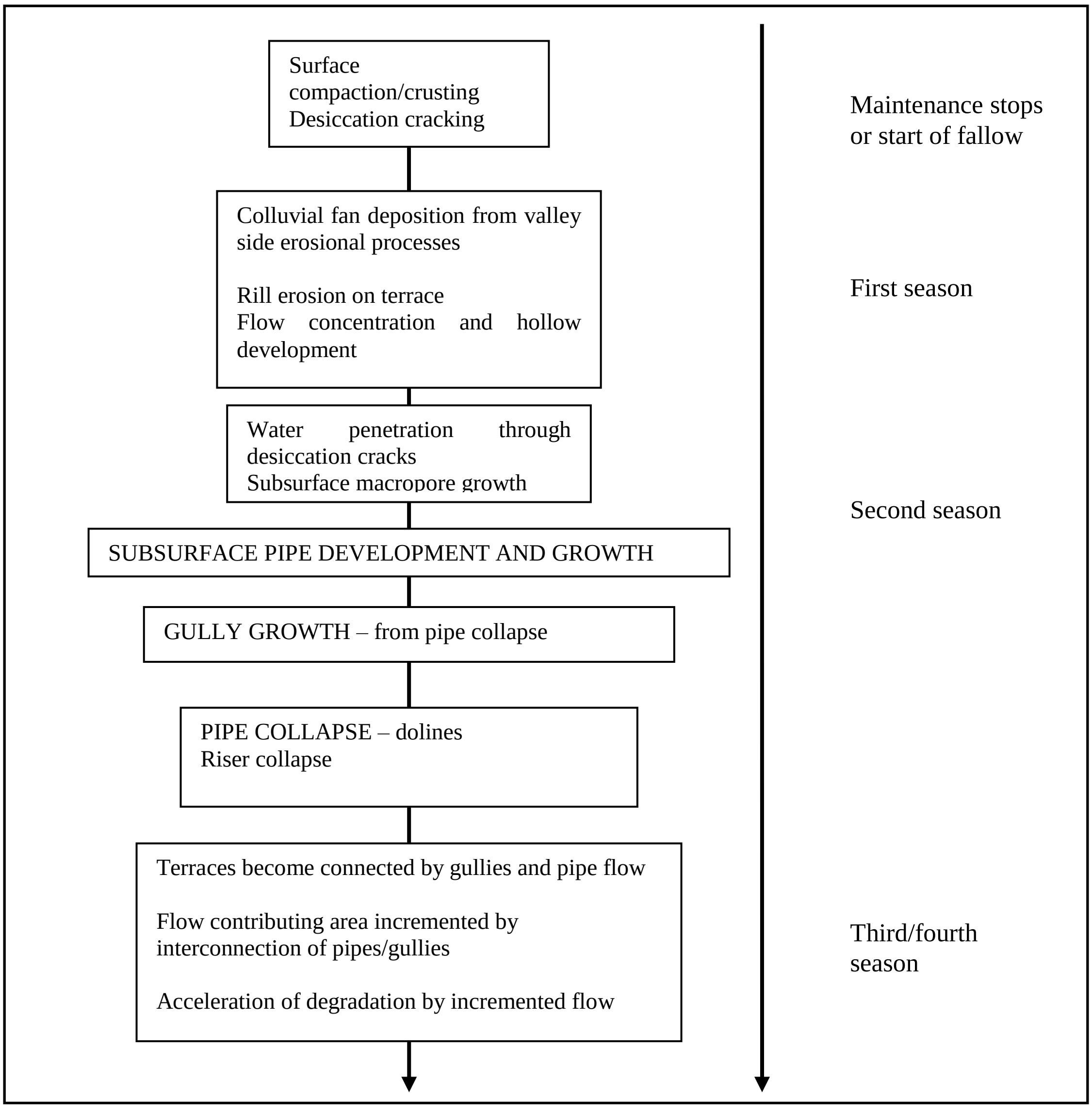


Figure 2.15 Terrace degradation sequence from Thompson and Scoging (1995)

Pipe collapse occurs when the pipes become too large for the surrounding material to support. These collapsed pipes continue to channel water and material as gullies. Thompson and Scoging (1995) found that concentration of water above the downslope terrace wall was a major causative factor in pipe and pipe collapse location and localised collapse of the terrace wall. Eventually the terraces are replaced by a new integrated erosional network which replaces the man-made terraced valley topography.

Thornes (1998) holds a more positive view on terrace abandonment, that in the long term, abandonment of agricultural land and its revegetation will reduce runoff and erosion under the present dry climate. The new vegetation will have a stabilising effect and that much of the damage done by erosion occurs as a result of high magnitude low frequency events rather than as a result of lower magnitude, more common events. Research has been carried out in the past ten years indicating that the Mediterranean region is not as subject to as high rates of soil erosion as previously thought, but the erosion rates on agricultural land that is being farmed in the new ways described below are higher than ever (Allen, 2001).

2.9.2.3 Terraces – the future

Thompson and Scoging (1995) observed that when they returned for follow up study of the terrace suite at Turré they found that major remedial work was in the process of being carried out on the terraces. This is currently happening in many places in the study area due to E.U. grants for planting olive and almond orchards as commented on in section 2.5.1.6 above. The levelling of traditional terraces to make larger fields, accessible by machinery implies a general steepening and lengthening of slopes. This entails an exponential increase in runoff which has the obvious consequence of accelerating erosion (Barth, 1995). In test fields in the Sierra Alhamilla the amount of soil erosion is in the order of 80-150 tonnes per hectare per year. This can peak at 500 t/Ha/year in conjunction with severe rainstorms (Barth, 1995). According to Barth (1995) these rates are higher than should be expected using one of the classical Soil Loss Equations and so it could be expected that soil erosion at this rate will create severe erosion problems in the near future, equable with badlands currently extant in the region. These new terraces will have to be managed carefully to ensure that they do not lose so much soil that they become barren.

As more of the land in the Sorbas Basin is brought into production from abandonment or intermittent use it may be useful to try and understand what some of the consequences of this might be. Obviously the demand for water is growing with every field planted with drip-fed crops. As on the coastal plains, this is going to have a similar effect – groundwater drawdown due to low rates of replenishment and salinisation by ground water drawn from marine sediment aquifers. Some parts of the field area have been bulldozed during the period of study (since 1996) and it is quite obvious that some of the roads built to service the new areas of agriculture are unstable after rainfall, with doline depressions and gullying appearing after precipitation. Observation of the new style 'pseudo-terraces' constructed in the Sorbas basin indicates that rills and gullies also appear here after rainfall, and these are ploughed back into the soil by the farmers. At the moment it seems likely that this agricultural development will continue without any environmental safeguards, subsidised by the E.U. making it attractive to those landowners who have not yet taken up subsidies. It appears that this type of agriculture is unsustainable, firstly due to removal of groundwater, secondly because of the apparent soil loss. Monitoring of the situation needs to be undertaken but unfortunately is beyond the scope of this thesis.

2.9.2.4 Human activity in the field area

Both the Rambla del Mocatán to the west and the Barranco Infierno to the east (see Figure 2.13) show evidence of old terraces, but there are no easy means of dating these terraces. Many of them contain very large olive trees, some of which are dead or dying. Olive trees commonly have a lifespan of 1000 years or more, with some olives trees recorded as being over 2000 years old, for example those in the Garden of Gethsemane near Jerusalem (www.oliveaustralia.aust.com). Without dendrochronological dating of olive trees in the two catchments it is impossible to say how old the trees are with any great accuracy, but the sheer size of some of the trees would appear to indicate that they have been in place on these terraces for a number of centuries. The nature of the older terraces in both of the catchments is very similar. The terraces themselves are generally small, between 300m^2 and 1000m^2. Approximately 20% of the old terraces contain olive trees which are still alive. Examples of these terraces are shown in red in Figure 2.16

There appear to be two other types of terraces/fields in the field area. There are larger, more regularly shaped terraced fields, mainly found in the Mocatán catchment. These have areas of between 1000 and 2000 m^2 and are in better condition than some of the smaller terraces. Many of these terraces have more than one large olive tree on them It can be hypothesised that these larger terraces have been created by amalgamating two or more smaller terraces (hence more than one olive tree) to allow for machinery to be used more easily (Barth, 1995). The third type of terrace shown on Figure 2.16 is more of a field, or a 'pseudo terrace' (Grove and Rackham, 1998). These are the type of fields that are carved out of existing terraces and hillsides to make enough room for the E.U subsidised groves of olives and almonds which are grown using drip feed irrigation. The size of these fields varies between 10 000 m^2 and 40 000m^2

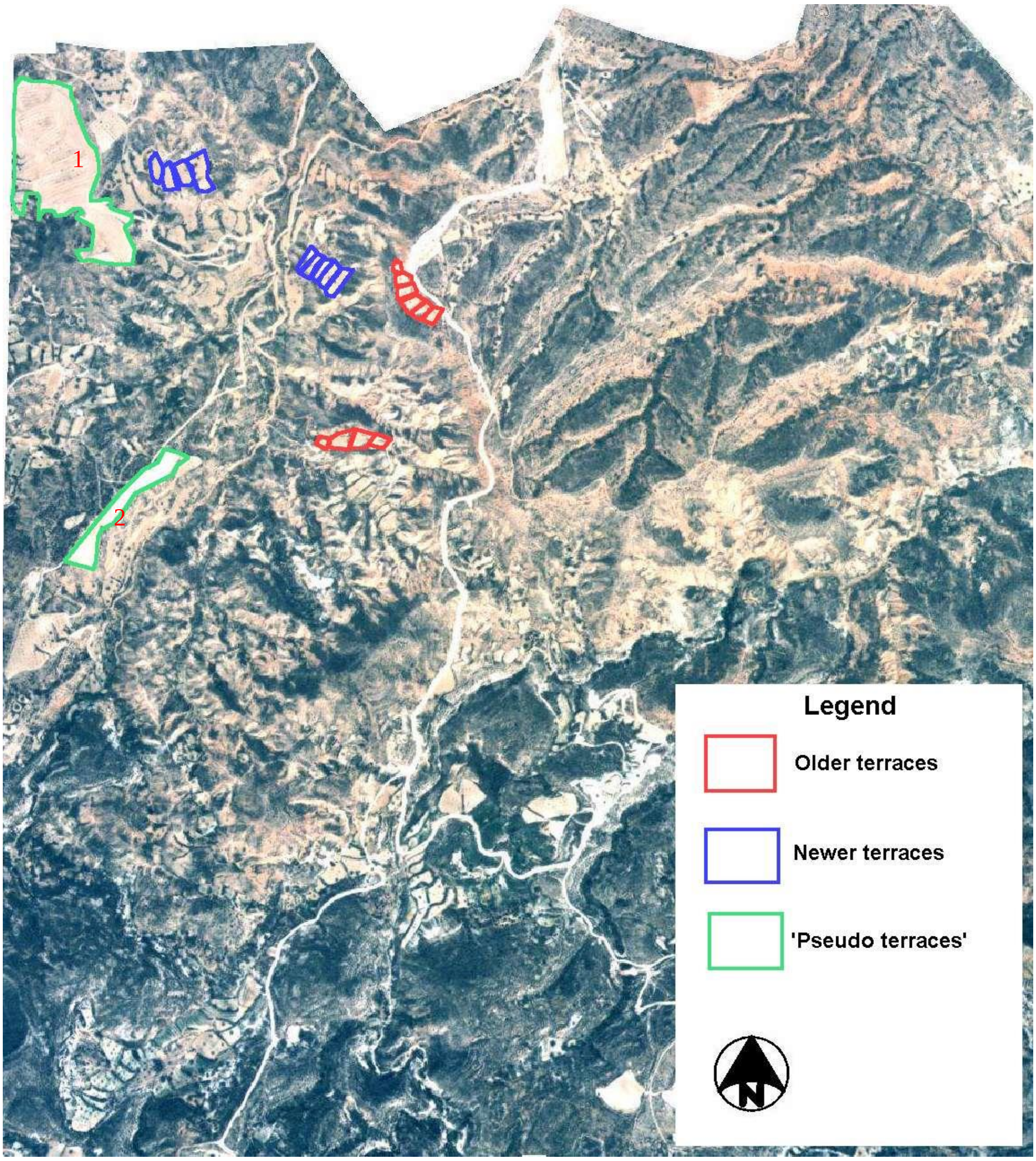


Figure 2.16 Aerial photograph of the Mocatán and Infierno catchments with annotations showing different field types

2.9.2.5 Agriculture and land use in the Barranco del Mocatán

Over the four year period of fieldwork, it has been observed in the Mocatán catchment that some of the more accessible older terraces have had sparse crops of wheat planted, or have been ploughed. This can probably be attributed in part to the fact that the Mocatán catchment has roads leading into it from both the east and west sides of the valley making access to the terraces in the catchment relatively easy. It has been observed that springs in the Mocatán channel are utilised for agricultural irrigation.

Some of the old terraces in the Mocatán catchment are in a poor state of repair. Flights of terraces have been dissected by very large pipes and gullies which means that they no longer act in as efficient a manner as possible as the downslope terraces are cut off from the upslope terraces and therefore do not get the delivery of runoff that they were designed to. A good example of this is described by Spivey (1997) where a stream capture has resulted in piping and gullying several metres deep, essentially leaving a terrace suite disconnected from the drainage network see (Plate 2.2). In another example, a single terrace is all that appears to remain at the top of what was once a suite of terraces which have now all been eroded, and reintegrated with the valley's drainage network as described by Thompson and Scoging (1995). As described above, there appear to be several suites of terraces that are more regular and approximately twice as large as the old terraces. These terraces are more regularly cultivated than the smaller older terraces, and in much better repair, and it appears that this was a modernisation attempt prior to the newest terraces, as described below, being built.

It has to be remembered that the Mocatán catchment is still undergoing incision from the base level changes caused by the capture of the proto-Feos by the proto-Aguas as described in section 2.3. This means that the terraces here need to be maintained perhaps more carefully than terraces in a catchment that is in equilibrium would need to be. The base-level change and the incision that it is causing is responsible for the aggressiveness of the erosion of the terraces, and the stream piracy which results in, for example, the extreme nature of the piping seen in Plate 2.2

2.9.2.6 New agricultural landuse in the Mocatán catchment

The western part of the Mocatán catchment is undergoing the process of modernisation as described above. Since the aerial photographs were flown in April 1996 there has been an increase in the number of the large 'Pseudo-terrace' fields, encroaching on the field area from the north and west where access is easiest. Cash crops are now being grown on these fields. On Figure 2.16 the numbers 1 and 2 in indicate where groves of drip-fed olives have been planted.

During a visit to the area in Spring 2000 it was observed that in several places, borrow pits were being dug for the extraction of material to make roads into the catchment. There was also a large warehouse/packing centre being erected next to where the Rambla Mocatán joins that Rio Aguas which indicates that the growing of crops in this area makes the time and effort and cost of this construction worthwhile.

Plate 2.2 Piping and gullying cutting across a terrace suite in the Mocatán catchment

2.9.2.7 Agriculture and landuse in the Barranco del Infierno

In the Infierno catchment, there has been little evidence of any planting or work done on the terraces over the four year observation period. This could be to do with the fact the Infierno catchment is less accessible than the Mocatán catchment. Springs in the Infierno catchment are not currently used for any irrigation purposes, although abandoned terraces are to be found right next to one of the only sources of running water in either catchment. Wells in a state of disrepair have also been observed in the Infierno catchment, so it is obvious that water harvesting was used once in this catchment for growing crops. It has been ascertained that the Infierno catchment is part of a *haçienda*, or estate which was abandoned approximately 60 years ago (Walsh, pers. comm.) which would explain some of the differences between this catchment and the Mocatán catchment. No-one appears to have responsibility for this catchment so therefore there is no interest in the upkeep of the terraces. The only observed uses of this catchment have been beehives set on a ridge near the main track that runs along the watershed between the two catchments, and some evidence of grazing.

The terraces in the Infierno catchments are in various states of disrepair. The stone fronting of the walls has fallen down in many places and the flood outlets of the terraces have been exploited by runoff and formed gullies, some of which are over two metres deep (Plate 2.3). Sideslope rills and gullies have formed, bringing debris onto the surfaces of the terraces, channelling runoff into the centre of the terraces and leading to the formation of pipes behind the terrace downslope walls as described in Thompson and Scoging (1995). This is shown in Plate 2.4.

The observed erosion has happened since the abandonment of the land as the rills, pipes and gullies are superimposed onto the terraces. It can be hypothesised that whilst the terraces were maintained, the catchment was in a form of equilibrium, but, when the maintenance ceased, terrace degradation, as described in Thompson and Scoging (1995), began to occur, and it still in the process of happening. Terraces downstream in the catchment are more eroded with deeper gullies than those upstream. In the terraces at the tops of the valleys, there is little evidence of erosion.

Plate 2.3 Gullies exploiting old terrace overflow channels in the Infierno catchment

Plate 2.4 Sideslope rills and gullies in the Barranco Infierno

The effect of the abandonment of agriculture in the Barranco Infierno has been to initiate a wave of erosion up the channel in this catchment which had stabilised after the original wave of incision from the base-level change due to the river capture. It is possible to observe areas in the catchment where the main wave of incision has cut into the Gochar sediment and then stabilised, a terrace has been built, and then abandoned, and a second wave of incision has cut into the terrace. There are questions that need to be asked about this erosion. Firstly, if the terraces were left unmaintained, would they eventually reach the final stage of Thomson and Scoging's (1995) model, that of reconnection with the valley drainage? Secondly, would this wave of incision cease once this reconnection had taken place – would a form of equilibrium occur. Thirdly, if these two waves of incision are visible in the landscape, does this mean that they have been the only two, or have there been others who's mark on the landscape has been erased. These are all question which are unfortunately beyond the scope of this thesis, but could form the basis of future work.

2.10 Summary

Chapter 2 identified the components that influence the environment of the study area. The climate geology and geomorphological setting were discussed. The limiting factors of semi-arid areas for plant growth were characterised with reference made to vegetation found in the Sorbas basin and the study are in particular. The historical summary of landuse in south-east Spain then examined how the landuse, specifically terracing, has had a significant impact on the way the landscape appears today. Chapter 2 identifies the factors that have driven the development of the landscape and sets the scene for the investigations into the landscape of the study area.

3 DESCRIPTION AND ANALYSIS OF VEGETATION IN THE STUDY AREA

3.1 Introduction

This chapter discusses vegetation description with emphasis on those techniques that were used whilst collecting data in the field area, and reports the results of the data collection. The second part of the chapter discusses vegetation analysis techniques and reports the results of analysis of the data using DECORANA and TWINSPAN. It should be noted that as the main purpose of the field work was to collect structural vegetation data to ground-truth remotely sensed imagery, some of the collection techniques used were adapted to fit with these aims and the resolution of the remotely sensed data. After the vegetation of the field area has been described a discussion of vegetation investigation and classification techniques takes place with particular reference to those techniques used to analyse the data collected in the field area. Results of the analysis of the vegetation data from field area are then discussed.

3.2 Vegetation data collection

There are two types of vegetation data which can be collected in the field; physiognomic and floristic. Physiognomic data provide information on the form and structure of natural communities. Floristic data provide information on the individual plant species that make up the vegetation in the area of interest (Kent and Coker, 1992). Physiognomic and floristic data were collected in the field using different methods and are discussed below.

3.2.1 Physiognomic data collection methods

According to Kent and Coker (1992) physiognomic and structural methods of data collection are usually used at the small scale (i.e. over large areas) to identify communities. Collection of physiognomic information is much faster than collection of floristic data. It is also a much easier technique to carry out for a researcher who is not familiar with the plant species in the area, and is very useful in areas where there are no floras to allow identification of plants (for example, many rainforest areas have undocumented plant species).

One of the major drawbacks of physiognomic sampling techniques is that the basis for sampling is rarely discussed. Physiognomic description of vegetation is usually made in an area that the researcher considers typical/representative and so this process can be accused of being subjective (Kent and Coker, 1992). This raises the question of what is a representative sample in physiognomic surveying.

3.2.2 Floristic data collection methods

The description of vegetation at a floristic level means that individual plant species have to be identified. According to Kent and Coker (1992) floristic description raises three main problems, the first being the identification of plant species, the second being whether or not to collect abundance data for each species and the third being the problem of where and what to sample.

Plant species identification can be achieved either through use of a relevant flora or by experience of working in the particular vegetation communities that are being sampled. The usual means of sampling vegetation is by using a quadrat which is traditionally a square used to establish a standard area for investigating vegetation within a set boundary. Braun-Blanquet (1951) developed an approach for optimising the size of a quadrat in any given vegetation community by developing the species-area curve which is arrived at by doubling the size of the quadrat until no more new species are identified at the next doubling in size. This works well in areas of homogenous vegetation, but does not work well in areas where there is patchy vegetation as edge or ecotone vegetation will be found in the quadrat as it gets larger and the nature of the environment will not allow a levelling off of the species area-curve (Forman, 1995; Goodall, 1961). Kent and Coker (1992) give general guidelines on selection of quadrat size for vegetation type when not using the species-area curve, for example heath and grassland communities should be surveyed with 2-4m^2 quadrats and scrub should be surveyed with 10m^2 quadrats.

The decision on whether or not to obtain abundance data for the species identified will depend on how quickly data need to be acquired, and what the final use of those data will be. Presence/absence data are quick to obtain, subjective abundance data are slower to obtain and objective abundance data are the slowest to obtain. Presence/absence data, as the name suggests, simply involve making a list of the plant species found in the area sampled. Subjective abundance data collection is carried out by estimating by eye the cover of each species. A number of subjective scales can be used; the DAFOR scale (dominant, abundant, frequent, occasional, rare), the Braun-Blanquet scale and the Domin scale (see Table 3.1). The Braun-Blanquet and Domin scales are somewhat more useful than the DAFOR scale as they can be converted into figures to be used for statistical analysis of the data collected.

It is likely that whilst recording flora using a subjective method of abundance assessment, a recorder will overestimate species which are in flower and are known, and underestimate others (Kent and Coker, 1992). However, it has been recognised in studies that measured the same vegetation using different techniques of abundance measurement, that those assessed subjectively were a good approximation of what was measured objectively (Smartt *et al*, 1974, 1976).

Value	Braun-Blanquet	Domin
+	Less than 1% (Scattered individuals)	No measurable cover (1 individual)
1	1-5%	1-2 individuals
2	6-25%	Several individuals but <1%
3	26-50%	1-4%
4	51-75%	4-10%
5	76-100%	11-25%
6		26-33%
7		34-50%
8		51-75%
9		76-90%
10		91-100%

Table 3.1 Braun-Blanquet and Domin cover scales (From Kent and Coker, 1992)

Objective measures of abundance include density counts, frequency, cover estimation using a pin frame and line intercept methods. The density of species is a count of the numbers of individuals found in a quadrat. Measurement of species density is generally used for population description rather than the description of whole communities. It is a time consuming technique and is entirely dependent on quadrat size. Measurement of frequency is the probability of finding a species in a given sample area. This involves throwing a number of quadrats in an area and recording the presence or absence of species. For instance, throwing 100 quadrats and finding a species in the quadrat 48 times gives a species frequency of 48%. Objective cover measurements can be found by using a pin frame which consists of a frame with a row of (usually) 10 pins held in it. The pins are lowered onto the vegetation and where the pin touches a plant, that species is recorded. This method is not useful in tall or shrubby vegetation, is time consuming and affected by patterns in the vegetation (Kent and Coker, 1992). Line-intercept methods of species analysis are useful in areas where vegetation is sparse, for example in arid areas. A tape is laid out and all plants touching the tape are identified and recorded. Percentage cover can be collected by measuring the length of the line touching each type of species or ground cover. Other methods of floristic data collection include measures of biomass, yield and performance.

3.2.3 Methods for sampling vegetation

Choosing the right sampling method for the type of study that is being carried out is very important. Issues such as time and resources will play a part in determining which sampling technique is used. A short review of random and stratified random sampling techniques is set out below. Other techniques for sampling are available, these include systematic, transect and plotless sampling, but as these techniques were not chosen for use in the field area they are not discussed here. For more details see Kent and Coker (1992).

3.2.3.1 Random, stratified and stratified random sampling techniques

The basis of random sampling is that every point in the study area has an equal chance of being chosen on each occasion a sample is taken. In order to sample an area randomly, a grid needs to be laid over the area to be sampled and then random co-ordinates to this grid need to be generated to give points for sampling. Samples are then taken at the random points using whichever sampling method has been chosen. The principle of stratified sampling is that the vegetation cover to be sampled is broken up on the basis of visible variations within it. Sampling then takes place within each vegetation cover type that has been recognised. Stratification is normally carried out by initial reconnaissance of the area to be studied, or by study of aerial photographs of the area in question (Kent and Coker, 1992). Divisions of the area to be sampled can be made on the basis of vegetation cover density, vegetation cover structure, or non-vegetation attributes such as aspect or geology. Stratified sampling saves time and effort whilst in the field, and ensures that all visibly different cover types are sampled where a different approach may mean that a visible difference in cover is not sampled. A variation on stratified sampling is stratified random sampling which is where sample points are shared proportionally among the main cover types present and then allocated at random within those categories (Allaby, 1994).

3.3 Techniques used in the field

There are four main points which need to be raised during planning a survey of vegetation in the field (Kent and Coker, 1992). These consist of; what is the purpose of the survey, what is the scale of the study, what is the overall habitat type and what are the resources available? The answers to these questions determine the type of survey that is to be carried out. The first question – what is the purpose of the survey - is probably the most important as this will determine the overall scale and habitat type that is to be surveyed. The final question – what are the resources available – has to be considered carefully as well because the amount and type of surveying is limited by time and the number of people available to carry out surveying.

Surveying in the field area had the primary aim of providing ground-truth for the interpretation of Airborne Thematic Mapper (ATM) data which were acquired in April 1996 (see Chapter 5 for details of ATM data and ground-truthing). The extent of the area to be studied including parts of two catchments, was approximately 1.6 x 2km (Figure 2.13). The overall habitat type was determined by the study area and was mostly semi-arid sparse *Mattoral* cover. The issue of resource availability was probably the most important fieldwork issue as this was both time and personnel dependent. The field survey had to be carried out at the same time of year as the remotely sensed imagery was acquired and there was only one person in the field to do the surveying so the methods used needed to be quick and easy to carry out.

3.3.1 Vegetation sampling strategies as used in the field area

One of the main decisions to be made before going into the field area was whether it was necessary to identify all plant species. As reported in 2.8 the vegetation in the field area is sparse and patchy in nature. The structure of the vegetation is of low to medium height woody shrubs, some tussock grasses and soft grasses and annuals. The sampling strategy primarily needed to identify vegetation characteristics which could be picked up by airborne remote sensing equipment. It also had to be suitable for the type of vegetation and easy to carry out. It was decided to collect both physiognomic and floristic data from the field during the field seasons in 1997, 1998 and 2000. Physiognomic data sampling techniques were used to collect ground-truth information from the field area for use with Airborne Thematic Mapper (ATM) data. The physiognomic sampling techniques used were adapted from techniques used in the field in south-east Spain by Alexander (unpublished) and Lazaro and Canton Castilla (pers comm) and Canton Castilla (1999). Floristic data were collected in order to examine the influence of environmental variables other than those which can be determined using remote sensing and to provide for the analysis of more subtle variation. The physiognomic data collection techniques used were more objective than the floristic data collection techniques. Both techniques are set out below.

3.3.1.1 Physiognomic sampling technique

A quadrat method of sampling was used to collect vegetation data in the field area. There was a conflict between using the right quadrat size (Kent and Coker, 1992) for sampling the shrubby vegetation, and the right quadrat size for ground-truthing the ATM data. The correct quadrat size for shrubby heath communities is between 2 and 4m². However, 15x15m quadrat or training areas[1] were used to collect physiognomic cover data from homogeneously vegetated areas for ground-truthing, as the ATM data had a 5m pixel resolution and thus each 15x15m training area would enclose at least one ATM pixel. Using a training area 2-4m² in area would not have worked in this case. In each training area cover data were collected along a series of 16 transects of 15m length. A cover reading was taken at 1m intervals along each 15m transect in the training area, meaning that 256 readings were taken in each training area (see Figure 3.1). Cover was recorded in 11 different classes, 9 vegetation and 2 non-vegetation cover types as listed in Table 3.2. These classes were selected after discussion with researchers from the Estácion Experimental de Zonas Aridas in Almería who were carrying out similar work in a nearby badland site (Canton Castilla, 1999).

Stratified random sampling was used as the cover in the field area is very patchy and fragmented. The patches are also small, the mean patch size being approximately 0.02 ha and thus randomly distributed samples would have a likelihood of containing heterogeneous cover. Stratified sampling enabled particular types of cover to be chosen from aerial photographs before visiting the field area. Four main cover types were established by aerial photograph interpretation before going into the field. These were dense cover, medium cover, sparse cover and bare/agricultural ground (Figure 5.4 and section 5.5.1).

Cover type	Cover Description

[1] A quadrat is also known as a training area when used for collecting ground-truthing information as the data collected are used to ‘train’ remotely sensed imagery for classification purposes.

Bare Silt Crust	Bare sediment, either crusted or uncrusted; includes bare soil
Stones	Stony surface bare of lichens or mosses, may be loose or cemented or a calcrete crust
Organic Crust	Black or brown algal or cyanobacterial crust on the ground surface or on stones
Lichens	Lichens found on stones or on bare ground. Mosses also included in this category
Grasses	Short soft grasses which are either single stemmed or grow as bunches but not tussocks
Annuals	Annual plants, soft-stem short perennials and plants grown from tubers/bulbs
Shrubs > 35cm	Woody stemmed plants over 35cm in height
Shrubs < 35cm	Woody stemmed plants under 35cm in height
Litter	Dead plant litter either standing or on the ground
Clump grass > 35cm	Multi-stem tussock grasses above 35cm in height
Clump grass < 35cm	Multi-stem tussock grasses below 35cm in height

Table 3.2 Cover types recorded in the field

Three of these cover types were then sampled. Bare or agricultural ground was not sampled, as it was easy to identify and map from the aerial photographs and was expected to be similarly distinctive in the ATM data. The biggest problem for selection of sites in the field was finding areas of homogenous cover large enough for a 15x15m training area. The aerial photograph was used in the

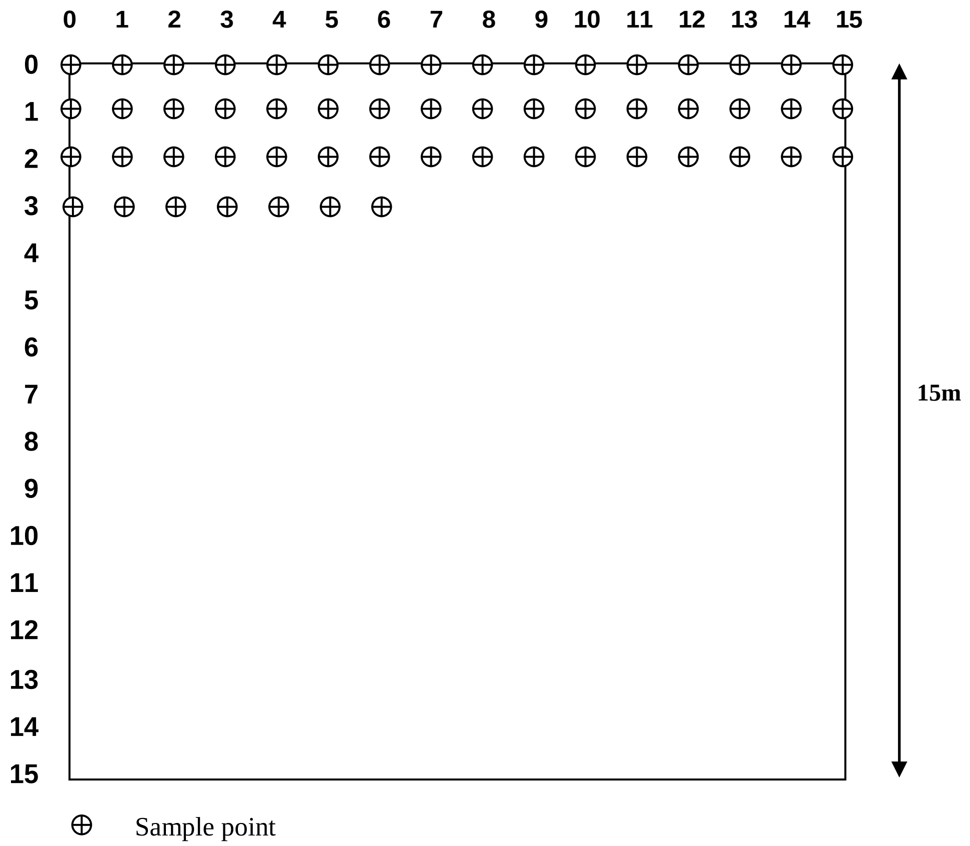


Figure 3.1 Layout of transects in cover recording quadrats

field to identify likely areas of cover. When one of these likely areas was located and was found to be large enough to place a 15m x 15m training area within it, a rock was thrown into the area, and its point of fall was taken as the north-east corner of a quadrat. If a quadrat of that orientation did not fit within the area, the point would become the north corner of the quadrat, and thus not all quadrats had the same orientation. It was sometimes difficult to find areas of homogenous cover of 15x15m extent due to the small size of patches in the field area.

3.3.1.2 Floristic data collection

Floristic data were collected in the same 15x15m quadrats on an 'estimation-by-eye' basis. The Braun-Blanquet scale (as described in Table 3.1) was used to record the relative abundance of each species identified. It is likely that some of the smaller species were missed during this estimation by eye as the areas were large, and the recorder inexperienced in plant identification at the start of the project. However, as described in 3.2.1.1 above, estimation by eye gives a reasonable assessment of the actual percentages of species type.

In the 2000 field season 3x3m quadrats were used for more detailed investigation of the floristic data, and to confirm the ATM data classification (see Chapter 5 for more details). The estimation was carried out in the same way as described above using the Braun-Blanquet scale. Physiognomic cover in 2000 was also recorded for use with the remote sensing data but in this case the physiognomic cover was also recorded by eye.

3.3.2 Description of field methods

3.3.2.1 1997 and 1998 fieldwork

Figure 3.2 shows the recording sheet used for data collection during the 1997 and 1998 field seasons. One column of the recording sheet was completed for each transect using a tally count. At every metre point, the cover seen directly below the tape was recorded in the correct box. The sheet was also used to record other variables. These were slope, aspect, cover class type (sparse, medium or dense), soil colour (using a Munsell colour chart), penetrometer readings for bare silt crust and organic crust. A further section was used to record the identity and amount of each plant species found in the quadrat, and other observations. There was a section to record the rover file number from a handheld GPS. GPS readings were taken from the north-east corner of each training area for accurate positioning at a later stage. A photograph was taken of each quadrat for future reference, and the recording sheet contained a place to record the photograph number. Samples of crust and soil were taken from the north-east corner of each plot at the surface for crust and at depths of between 10 and 30cm and returned to the UK for analysis.

Survey no Location Class GPS reading Date Time

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	Total	%
Bare silt																		
Bare soil																		
Stones																		
Organic crust																		
Lichens																		
Grasses																		
Annuals																		
Shrubs>35cm																		
Shrubs<35cm																		
Litter																		
Stipa>35cm																		
Stipa<35cm																		

Penetrometer
BSC Org

Aspect

Slope

Munsell

Photo

General description of vegetation

Other Observations

Figure 3.2 Recording sheet used in the field in 1997 and 1998

3.3.2.2 2000 fieldwork

The fieldwork carried out in 2000 had a slightly different emphasis from that carried out in 1997 and 1998. Its purpose was to provide data suitable for checking the results of the ATM analysis (see Chapter 5) and so the quadrats did not have to be 15x15m. A quadrat size of 3x3m was chosen which coincides with the size of quadrat indicating as being useful for shrubby heath communities by Kent and Coker (1992). These quadrats were stratified on a slightly different basis to those in the previous two year's fieldwork as the cover in the field area had been divided up into six classes on the basis of an analysis of the remotely sensed data. These six classes were dense, layered vegetation; shrubby vegetation with most shrubs over 35cm; clump grass and stony cover with small shrubs and a little bare ground; small shrubs and a lot of bare ground; and two types of mainly bare ground sediment, one with a less reflective underlying sediment with a few small plants, the other with a highly reflective underlying sediment and few, if any, plants. Quadrats were recorded in all but the last class. Figure 3.3 shows the recording sheet used for this investigation. Cover data were acquired by making a visual estimate of percentage cover of each cover type. The number of species within each cover type found in the quadrat was also recorded. Other information recorded included soil colour (using a Munsell colour chart), slope, and aspect. The following observations were also made at each quadrat: distance to the nearest drainage line, distance to the nearest actively eroding area (if not the same), extent of quadrat vegetation cover connectivity to the rest of the vegetation around it, and type of site (remnant, recolonising, old/new, other) . A detailed floristic survey of these quadrats was carried out with all species found being recorded together with Braun-Blanquet abundance figures. Determination to species level proved impossible for a small number of plants. These were identified to genus or in some cases, only to family level. Results of the data collection are reported in section 3.5.

Survey no | **Location** | **NDVI6 class** | **GPS rover number** | **Date** | **Time**

	Total % cover	No of species	Grasses	Annuals	Big Shrubs	Small shrubs	Clump grasses
Bare Silt							
Stones							
Organic crust							
Lichens							
Grasses							
Annuals							
Shrubs >35cm							
Shrubs<35cm							
Litter							
Clump grass>35cm							
Clump grass<35cm							

Aspect

Slope

Photo number

Braun-Blanquet scale
x - scattered
1 0-5%
2 5-10%
3 10 - 25%
4 25 - 50%
5 50+%

General description of training area

Other observations

Figure 3.3 Recording sheet used in 2000

3.4 Methods of investigating vegetation data

As discussed above, surveying in the field area was carried out with the primary aim providing ground-truth for the interpretation of Airborne Thematic Mapper data. However a secondary aim could also be addressed by the collection of cover and floristic data; that of an ecological survey of the floristics and cover types within the field area and analysis using vegetation science techniques which are discussed in this section. By using the data acquired during fieldwork, an analysis of the structure of the cover in the field area could be undertaken by applying the standard vegetation science techniques of ordination (DECORANA) and classification (TWINSPAN) to the cover data rather than floristic data. By collecting floristic data concurrently with physiognomic data, additional information that would not be available from remotely sensed imagery could be investigated and add value to the cover observations made. Some methods for analysing vegetation data are discussed in the following section with reference made to the particular techniques used to analyse the cover and floristic data collected from the field area.

3.4.1 Vegetation ordination

Ordination, which means to 'set in order', is the arrangement of vegetation samples in relation to each other in terms of their similarity. Ordination is used to determine degrees of similarity and to investigate how the order of the individual samples is correlated with environmental controls. Ordination allows data reduction and the formulation of hypotheses concerning causal relationships between vegetation and environment. In plant ecology, ordination can be used to help the following research areas: summarising plant community data to provide an indication of the variation within the area being studied, enabling the distribution of individual species within the different communities to be examined and compared, and providing summaries of variation within sets of vegetation samples which can be correlated with environmental variables to help define environmental gradients (Kent and Coker, 1992).

There are three different uses for ordination; indirect vegetation ordination (also known as indirect gradient analysis) which is ordination derived only from vegetation data, environmental ordination which produces ordination axes derived from vegetation and environmental data, and summation of environmental variation independently of vegetation which is known as synthesis of environmental factors. These three different techniques produce different end products which are used in different situations depending on the data available and the assumptions about underlying environmental gradients. The technique used in this thesis involves only indirect ordination as the only information analysed through ordination was vegetation data. The ordination method used was DECORANA (DEtrended CORresondence ANAlysis (Hill, 1979a)). The section below provides a brief explanation of how ordination and correspondence analysis work, followed by an explanation of DECORANA.

3.4.1.1 Indirect ordination method

Indirect ordinations are based purely on the data collected about vegetation in the sample areas/quadrats without any other environmental factors being used to determine the outcome. The concern is with the internal variability of the data using the assumption that the internal variability will reflect variability in the environment (for example, geology, slope, aspect) when this is used in the interpretation stage. Most simply, ordination can be seen as a way to summarise information in a data matrix. However there is another view that there is a latent structure in the data matrix so that the pattern of species entries in the data matrix is determined by other environmental variables. Therefore the purpose of ordination is to discover the latent structure, and in doing so, to identify the environmental factors that the species are responding to (Kent and Coker, 1992).

Ordination diagrams are the end product of indirect ordination. Plots can be made along one, two, three or more axes, with the distances between samples on the graph taken as a measure of similarity (if close together) and dissimilarity (if far apart). Generally axis one summarises more variation than axis two and so on. Usually only the first three or four axes are of any significance, although it is theoretically possible to extract axes up to the number of species in the analysis. The process of ordination is illustrated by Figure 3.4.

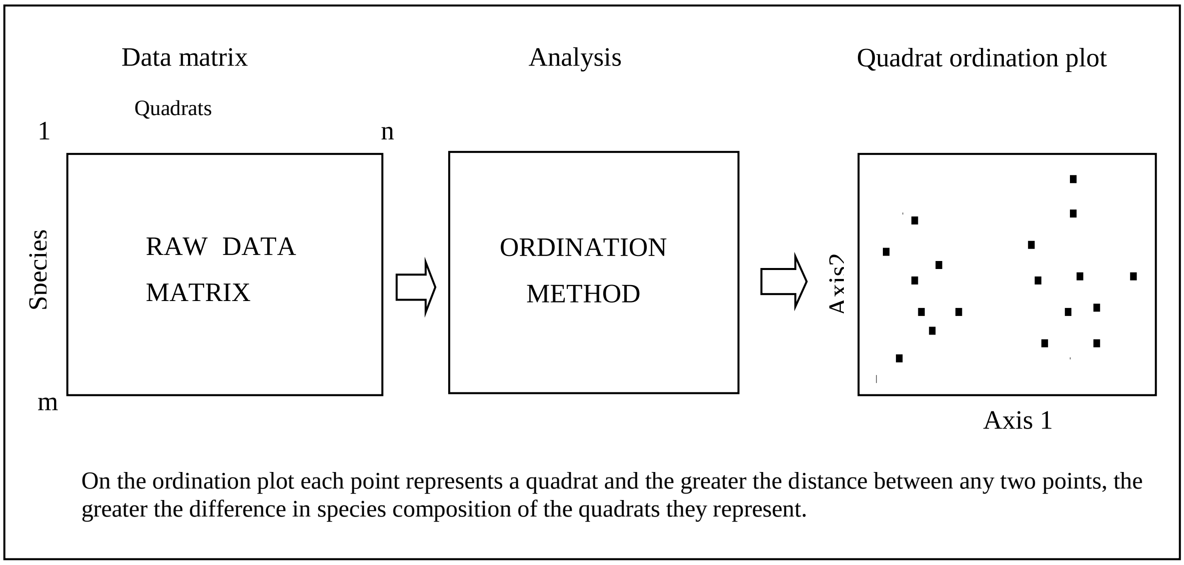


Figure 3.4 The process of vegetation ordination (from Kent and Coker, 1992)

After the axes have been plotted it is then possible to superimpose environmental data onto the quadrat ordination diagram. Examination of the diagrams superimposed with environmental data can lead to hypothesis generation and recognition of the influence of environmental variables on vegetation distribution. Relationships between the ordination results and environmental variables can then be tested through regression, correlation and other statistical analyses.

3.4.2 Correspondence analysis (DECORANA)

Correspondence analysis or reciprocal averaging is ordination with weighted averages along lines similar to Principal Components Analysis. It bases the ordination on the original data matrix so there is a simultaneous ordination of species and samples. A detailed worked example of the method is given in Kent and Coker (1992, pp 215-221). There are two major problems with correspondence analysis. Firstly, although the linear regression technique removes any linear relationship between the axes, the method leaves in a systematic relationship between them. This has the effect of producing an ‘arch’ when two axes are plotted together. The second axis is a quadratic expression of the first, and higher axes are higher order expressions of the same thing. Interpretation of the results becomes difficult as it is difficult to tell which axes contain meaningful ecological data. The second problem is that reciprocal analysis has the effect of "compressing" scores toward the ends of the axis relative to the middle. This is related to the arch effect.

Detrended correspondence analysis was conceived by Hill (1979a) and Hill and Gauch (1980) to solve the problems with correspondence analysis listed above. Detrending the data involved removing the quadratic relationship between axes which solved both the ‘arch effect’ and the problem of compression at the ends of axes. This led to the development of the DECORANA program for computers. There are criticisms of detrended correspondence analysis. Quadrats that are very different to the rest of the data, known as outliers, and gaps in the quadrat distribution along axes cause problems and can lead to inaccuracies in the results. These criticisms are dealt with in Kent and

Coker (1992) and the authors conclude that detrended correspondence analysis (and therefore DECORANA) remains a widely used and effective indirect ordination technique. It is as good as any other ordination technique currently available, and in some situations better, as long as the limitations are acknowledged.

3.4.3 Vegetation classification

Classification is a means of structuring data to group individuals on the basis of similar attributes (Allaby, 1994). Classifying vegetation data is a means of recognising and defining plant communities by grouping together a set of samples on the basis of their composition (Kent and Coker, 1992). The ultimate aim of a classification is to produce a set of end groups where the members of each group are more similar to one another than they are to members of any other end group (in practise this is rarely achieved). Classification is used in vegetation science by those who subscribe to a Clementsian (1916) view of plant communities/assemblages rather than the view of Gleason (1939) where all plants are seen as members of a continuum responding to different environmental gradients (Kent and Coker, 1992, Allen, 2001). Classification is an important component of phytosociology which is the categorisation of plant communities based on floristic considerations (Allaby, 1994). However, the concept of plant communities being in equilibrium with the climate and other environmental factors is now seen as somewhat simplistic (Allen, 2001). The idea of communities in equilibrium is giving way to a different viewpoint where associations of plants are seen as changeable depending on the environmental circumstances surrounding them. It is now considered by some that species that associate now did not necessarily associate with each other in the past, and may not do so in the future (Pahl-Wostl, 1995).

Much of the work on plants and plant assemblages in the Mediterranean region has been carried out by workers following the Braun-Blanquet school of vegetation classification (see below) which means that most of the literature about Mediterranean plant communities depends very much on the concept of phytosociology and species association. It is acknowledged that a change in attitude to the classification of plant communities is taking place, and the idea of a "Mediterranean plant community" does not actually exist in some other places with Mediterranean climates (for example, California) (Allen, 2001). However, because of the tradition of the Braun-Blanquet school in the European Mediterranean and the large amounts of literature using this form of classification, the original Braun-Blanquet (1939) type terminology will be used throughout the rest of this section.

There are numerous methods of classification of vegetation data. The earliest classification methods used were subjective in nature and were carried out by members of the Braun-Blanquet school from the 1920s onwards. After sampling, floristic data were sorted by hand, grouping like with like using 'differential' species to sort the data. The eventual outcome of this classification would be a synoptic table summarising the data for each association. This technique is very important in vegetation science as it paved the way for other methods of classification (Kent and Coker, 1992). This technique has many flaws, the greatest of which is the subjectivity of the method which involves the person sampling having a prior knowledge of the plant assemblages to be sampled. However, this method has been used to classify most of Europe's vegetation and appears to work well when used by knowledgeable plant ecologists. The use of computer programs from the 1950s has meant that the sorting of floristic data tables into like with like has become a lot less time consuming.

Numerical classification methods are used to look for pattern and order in a set of data and are used to reduce and explore the data that have been collected in the field (Kent and Coker, 1992). This form of classification is often an end in itself, but it can be used for hypothesis generation leading on to more detailed research. Using computing power, thousands of samples can now be classified in one analysis compared to the sorting by hand method of the Braun-Blanquet school which became unwieldy after only a few tens of samples. Numerical methods of classification are objective as they can be repeated. Numerical classification represents a set of rules for a process of grouping samples together. However, this has meant that many classification techniques have now become available for use with computers, all of which are slightly different and give different end groupings. There is no single classification for any set of data, and it is up to the person analysing the dataset to chose the 'best' classification technique, i.e. the one that enables a clear ecological interpretation to be made.

Classifying a dataset should enable the natural group structure in the data to be found. Some datasets will fall more readily into groups, others will need to be forced which means that some samples will be misclassified as they don't fit the group structure properly. According to Kent and Coker (1992) the researcher needs to intuit that some sort of group structure does exist otherwise the classification will only randomly divide up a continuum.

3.4.4 Two-way indicator species analysis (TWINSPAN): an explanation and discussion.

TWINSPAN is one of the most widely used polythetic divisive classification packages currently available for vegetation analysis. The method was originally described as indicator species analysis in the paper by Hill *et al* (1975), but in his paper of 1979 Hill (1979a) comments that the description is confusing and the method would have been better described as 'dichotomised ordination analysis' as the method is based on a division along a first ordination axis, with the two divided groups then being divided along their first ordination axes and this process continuing until a set endpoint is reached. The method of division of the samples is based on DECORANA as described in section 3.4.2.

3.4.4.1 Polythetic and divisive methods of classification

Most classification techniques used over the last 30 years have been hierarchical in nature and TWINSPAN is no exception. This means that the results can be displayed as a dendrogram which shows similarity or dissimilarity at different levels and which is useful for ecological interpretation of the results. TWINSPAN is a divisive method of classification. Divisive classification starts with the total population of individuals and progressively divides it into smaller groups at different levels (which can therefore be displayed as a dendrogram as described). Division takes place at each level by dividing the number of species into two, so one group of species will be divided into two, two into four, four into sixteen and so on. Division stops either when single samples are left or at a level predetermined by the operator. The process of polythetic classification enables the allocation of samples to groups to be based on all the data available rather than just the presence or absence of one attribute. This is seen as an optimal approach to classification as all information collected is used in the classification process, but until the 1970s there were substantial technical and computing problems which did not allow the full development of this technique (Kent and Coker, 1992). Polythetic divisive methods are based on ordination techniques. This means that ordination space has to be partitioned and lines drawn through the area of the plot which has the lowest density. The best way of envisioning this is the placing of divisions through the least dense areas of points which represent quadrats in a multi-dimensional space allowing clusters of points to be grouped together into groups with similar attributes.

One of the most important aspects of TWINSPAN is the use of pseudospecies. Pseudospecies involves the use of different levels of abundance for a single species in the classification (Hill *et al*, 1975). The idea behind the use of pseudospecies is that in most classifications a binary analysis is used so it is just the presence or absence of a species that is used in the classification. The relative amount of a particular species in each quadrat is not accounted for. By devising the concept of pseudospecies, Hill *et al* (1975) allowed abundance data to be accounted for. For example percentage cover of a species may be cut into six different levels (e.g. 1-2% 3-5%, 6-10%, 11-20%, 21-50%, 51%+). Each of these 'cut levels' would be used as a separate species in the classification algorithm, so the abundance of for example *Stipa tenacissima* in a quadrat would be divided up into six species and recoded as

Stipa tenacissima 1	percentage cover 1-2%
Stipa tenacissima 2	percentage cover 3-5%
Stipa tenacissima 3	percentage cover 6-10%
Stipa tenacissima 4	percentage cover 11-20%
Stipa tenacissima 5	percentage cover 21-50%
Stipa tenacissima 6	percentage cover 50+%

If there was two percent cover of *Stipa tenacissima* in a quadrat then the pseudospecies *Stipa tenacissima* 1 would be present. If there was 55% cover of *Stipa tenacissima* cover in a quadrat then all 6 *Stipa spp*. pseudospecies would be present as the nature of the pseudospecies is that they are non-exclusive and cumulative.

3.4.4.2 Simplified explanation of the TWINSPAN classification method

TWINSPAN is a complex program and detailed description of its workings is beyond the scope of this thesis. Full explanation of the package can be found in Hill *et al* (1975), Hill (1979b), Jongman *et al* (1987) and Causton (1988). A somewhat more simplified explanation can be found in Kent and

Coker (1992). A highly simplified explanation of how TWINSPAN works derived from the above sources can be found below.

The basic premise of TWINSPAN is that with each division, one side of the division of quadrats/samples can be characterised by the presence of one set of 'indicator species' and the other side of the division can be characterised by the absence of these first indicator species and maybe the presence of another set of indicator species. Obviously this cut does not often happen neatly and there will be samples that are 'misclassified' as they may have some of both or neither set of indicator species. The process of division of the quadrats/samples happens in the same way at all levels of the classification.

A table is produced by TWINSPAN which codes the presence or absence of all species including pseudospecies. This means that there is a large amount of information produced. For example, if there were originally 100 species recorded during the survey and there are 6 pseudospecies required there will be a potential total of 600 species entered into the classification. As the pseudospecies are defined by abundance, the abundance information collected in the field is not lost even though the data go into the classification in a presence/absence form.

3.4.4.3 Primary ordination

Once the data have been entered into the program, a primary axis ordination is carried out, splitting the samples into a positive group and a negative group. The program then identifies which pseudospecies are found either exclusively, or more frequently on one side of the division. These are the indicator pseudospecies. A pseudospecies which occurs only on one side of the split is known as a perfect indicator and is given a value of 1 (+ or -) depending on which side of the division it falls. A pseudospecies which occurs in every quadrat will be given a value of 0. If a pseudospecies occurs on both sides of the divide, in all quadrats on one side but in only a few quadrats on the other it will be given a number between 0 and 1 depending on how much it falls to one side or across the whole range of samples. The TWINSPAN rule about the multiple pseudospecies is that the pseudospecies which has the highest indicator value becomes the indicator value for all cut-levels of that species.

3.4.4.4 Refined ordination

Each quadrat is then allocated an indicator score by adding +1 for every positive indicator and –1 for each negative indicator it contains and the scores are added up. An indicator threshold is set which then allocates quadrats to either the negative or positive side depending on their scores. In a modification of the original TWINSPAN program, Hill (1979b) added a transfer or iterative relocation algorithm in which a discriminant function is used to make transfers. This has led to a better polarisation of ordination and reduction in the number of borderline cases.

Misclassifications and borderline cases occur in what is known as the zone of indifference. This is where, for example, a quadrat has been placed into a negative group in the primary classification and then placed in the positive group by the refined ordination. It is usually found that misclassified quadrats are borderline, sitting in the middle of the ordination to start with and where they are allocated is a 'matter of indifference', so a small zone of indifference is defined in the original primary ordination where quadrats which fall into this zone can be examined by the program. This zone of indifference is moved gradually and the final optimum position is found where there are the fewest misclassifications.

3.4.4.5 Final division and output

The final division is decided by the program when the best fit for the quadrats is found in that the majority lie within ether a positive or negative group and there are as few misclassified and borderline quadrats as possible. All further divisions in the program are made in exactly the same way where the output negative and positive groups are each divided once again into negative and positive groups and so on. The program usually terminates when there are four or less quadrats in a group, but this figure can be varied at the start of the program. The TWINSPAN program produces a two-way table at the end of the TWINSPAN analysis (see Figure 3.5). This matrix represents a sorted two-way table of the original data matrix. Quadrats are sorted column-wise and species row-wise.

3.4.4.6 Explanation of the output table

Quadrat numbers are written vertically across the top of the table so in the example above it is possible to see that quadrat 9 is first, 32 second and so on. They are not sorted in numerical order, this is the result of the analysis placing them into groups. Abbreviated species names are written to the left hand side of the table. Again they are not in alphabetical order as a result of the sorting of the data by TWINSPAN. The table presents the sorted species and quadrat data. The overall effect of the sorting on the data should be a diagonal trend. This pattern does not show up in Figure 3.5 as the table is only part of the whole TWINSPAN table for this particular analysis. Species which do no fit into the diagonal trend will tend to be at the top or the bottom of the table. The numbers in the table from 1 to 3 correspond with the pseudospecies levels that were given at the start of the process. In this case 1 corresponds with ≤1% 2 with 2-10% and 3 with 26-100%. The zeros and ones at the bottom of the table indicate the group structure and sequence of divisions of the groups of quadrats. The first row of zeros and ones is split into two. This is the first level where the original group is split into negative and positive groups (0 and 1 respectively). The second row shows the split of the first negative and first positive groups into two more groups making four. The third row shows the split of the previous four groups into eight, and so on to the fifth level where there are only six groups from a possible 32 as some of the earlier groups were too small to split. End-groups can be identified by reading the values in the bottom section of the output vertically (i.e. 000, 0100 etc).

The interpretation of the output table is subjective. The endgroups of the classification can be taken as they are, or if they seem too small or artificially divided, they can be amalgamated back with the other quadrats that were in the group above. Using these TWINgroups after classification, statistical analysis can be carried out to discover the environmental variables that have a bearing on the classification (for instance the classification may reflect geology or aspect). TWINSPAN is a very useful tool for organising a great mass of vegetation data into a usable form and enabling this vegetation data to be analysed to determine the underlying reasons for its distribution.

TWINSPAN and DECORANA analyses of results for the cover and floristic data collected in the field area are presented in section 3.6.

```
                3234613345634451146  52445556  1412221236 2213  1234
               9221013794724363281057875904952378538910348140016465 24

  4 Aven hirt  221112--11-1---------1-------------------121---------  00
 10 Limo insi  2123333323332-222121122-1111111121212222222211-111--1  00
  2 Cras spp   23-2223332231222222132333232333333121112221 21--2233122  010
  8 Echi spp   1-2-11221222132212213322332312222211-1111212111 2222222  010
 11 Arte spp   1121-11111211-21-111---11111111-1121111121---31---111-  010
  3 Orga crus  21-2111-1-12----1222111221 2211---12-21122122211131122-  011
  7 Stip tena  1223332223223333333322222323331222222312223122222222 33  011
  9 Cist liba  2122222222222222222222122222222322323222232223322223 23  011
  1 Thym hirs  33---1---------------1-1--11-11-1121123231123-2111-11-  1
  5 Arte spp   --1--1---------------1-1-1--1--1-1211211111112321212 21  1
  6 fuma eric  -11-----11--11211-1----11111--1111232211-1112212122222  1

               0000000000000000000000000000000011111111111111111
               0000000000001111111111111111111110000000000011111111
               0011111111110000000011111111111110000111111100000000 0
                 0111111111000011110001111111111    0000111001111111
                  000111111           00000001111            0000001
```

Figure 3.5 Part of a TWINSPAN two-way table of results

3.5 Results of cover data collection

The cover data collected in 1997, 1998 and 2000 are reported in this section. The results are reported as a percentage cover score for the 1997 and 1998 datasets with each result being a percentage of the 256 cover readings taken in each training area. The 2000 cover results are reported as the percentage that was estimated by eye in the field. Table 3.3 shows the 1997 results, Table 3.4 shows the 1998 results and Table 3.5 shows the 2000 results. The training areas are numbered sequentially with 1997 having training areas 1-42 1998 having training areas 43-65 and 2000 having training areas 66-110.

All of the 1997 training areas were all collected in the Mocatán catchment as this was the area that the thesis was originally concentrating on. Three different cover densities were selected for sampling (as described in section 3.3.1) and a stratification was added in order to divide each cover density into slope, pediment and plateau to ensure a good spread of site types. However this stratification of site type was not carried over into the 1998 and 2000 fieldwork. The training areas for 1998 were all collected in the Infierno catchment as by then it had been decided to collect data from both catchments in order to compare and contrast them. The same three cover densities were sampled as in 1997; dense, medium and sparsely vegetated areas. In 2000, quadrats were sampled in both catchments.

Full listings of plant species data can be found in Appendix 1 along with the data collected for the other variables measured in the field.

It can be seen in the results Tables 3.3, 3.4 and 3.5 that in all years a wide variety of covers were sampled, from very sparsely vegetated to very densely vegetated. However, to get a clear idea of the variation in sites types sampled, quantitative vegetation analysis was needed. This was carried out using DECORANA and TWINSPAN.

Train – ing/ Area #	Bare silt crust	Stones	Organic crust	Lichens	Soft grasses	Annuals	Shrubs >35cm	Shrubs <35cm	Litter	Clump grasses >35 cm	Clump grasses >35 cm
1	0.4	15.2	2.3	0.0	13.7	17.6	23.0	14.1	13.7	0.0	0.0
2	2.7	55.1	0.0	0.0	0.0	0.4	3.9	11.7	22.3	3.5	0.4
3	0.0	33.6	0.0	0.0	2.7	0.4	19.1	13.7	29.3	1.2	0.0
4	0.0	12.5	0.0	0.0	1.2	5.5	41.8	5.5	32.0	1.6	0.0
5	0.8	37.9	2.3	0.0	0.0	0.0	18.0	27.7	10.9	2.3	0.0
6	3.9	21.5	36.3	0.0	2.3	1.2	8.2	7.8	18.0	0.8	0.0
7	1.2	7.8	1.6	0.8	4.7	7.4	53.9	5.9	16.8	0.0	0.0
8	2.7	0.8	15.6	2.7	2.0	3.1	28.5	1.2	19.5	23.8	0.0
9	35.2	19.5	13.3	5.1	0.0	0.0	4.3	2.3	12.9	5.9	1.6
10	15.6	0.0	2.0	0.0	20.3	7.0	21.5	0.8	30.1	2.3	0.4
11	43.8	2.7	12.5	0.0	2.3	3.5	4.7	0.4	18.8	9.0	2.3
12	0.0	6.3	2.3	0.0	0.0	3.9	60.2	0.4	20.3	6.6	0.0
13	0.0	35.9	0.8	0.0	0.0	0.0	14.5	5.1	10.5	32.8	0.4
14	1.6	40.2	4.3	0.0	12.5	17.6	7.0	9.0	7.4	0.4	0.0
15	6.8	1.6	15.6	0.0	6.3	22.9	9.9	3.1	27.1	1.0	5.7
16	0.0	11.7	4.3	2.0	62.1	0.0	15.2	0.0	4.7	0.0	0.0
17	0.4	37.1	0.0	0.0	0.0	2.3	16.4	15.6	23.8	3.5	0.8
18	0.0	15.6	9.0	0.0	0.0	0.0	30.5	19.9	19.9	4.3	0.8
19	0.0	18.0	0.0	0.0	3.9	5.5	27.0	25.4	16.8	2.3	1.2
20	9.0	18.0	20.3	0.0	1.2	0.8	16.4	3.1	13.3	15.2	2.7
21	16.8	19.5	9.0	9.0	0.4	0.8	2.3	6.6	14.8	11.3	9.4
22	0.0	13.3	25.0	2.7	3.9	4.7	17.2	5.9	12.5	13.7	1.2
23	1.6	5.9	0.0	0.0	0.4	42.2	21.1	2.3	14.8	10.9	0.8
24	39.5	3.5	12.5	0.4	0.8	5.5	6.3	4.7	5.9	9.0	12.1
25	0.0	21.5	0.0	0.0	10.5	5.9	46.9	0.4	7.4	7.0	0.0
26	0.0	43.4	3.1	0.0	1.2	6.6	18.0	8.2	16.4	0.8	2.3
27	2.7	38.7	17.6	0.0	3.1	1.6	7.0	12.5	13.3	0.0	3.5
28	0.8	2.7	12.9	0.0	4.3	9.0	19.1	0.0	45.3	1.2	4.7
29	10.9	4.3	1.2	0.0	24.6	5.1	27.3	0.8	13.3	12.1	0.4
30	18.8	0.0	0.4	0.0	28.1	3.5	7.0	2.7	37.5	1.2	0.8
31	0.0	27.0	5.5	2.0	0.0	0.0	27.7	0.0	7.4	28.9	1.6
32	33.2	29.7	3.5	7.8	0.0	1.6	15.2	0.0	0.8	0.8	7.4
33	44.8	5.7	6.3	0.0	0.5	0.0	10.4	3.1	15.1	7.3	6.8
34	0.0	4.3	0.0	0.0	0.0	1.6	58.6	1.6	25.4	7.0	1.6
35	0.4	4.7	7.0	0.0	5.5	13.3	24.2	14.8	29.7	0.0	0.4
36	1.2	1.6	2.3	0.4	22.3	18.0	32.0	2.3	18.4	1.6	0.0
37	0.0	39.8	0.0	0.0	0.0	0.0	17.2	6.6	5.1	30.5	0.8
38	9.8	7.8	3.9	0.0	7.4	5.1	46.1	11.7	8.2	0.0	0.0
39	0.0	28.9	0.4	0.4	0.0	1.2	25.4	2.7	14.8	25.4	0.8
40	0.0	18.8	2.0	2.7	0.0	0.0	30.1	0.4	14.5	31.6	0.0
41	0.0	21.9	8.2	0.0	0.0	0.8	38.3	7.0	10.5	10.9	2.3
42	1.6	5.1	5.1	0.0	7.8	9.0	44.1	5.9	20.7	0.0	0.8

Table 3.3 Training area cover data collected in 1997

Training Area #	Bare silt crust	Stones	Organic crust	Lichens	Soft grasses	Annuals	Shrubs >35cm	Shrubs <35cm	Litter	Clump grasses >35 cm	Clump grasses >35 cm
43	0.0	21.9	0.0	0.0	0.0	1.6	38.7	25.4	12.5	0.0	0.0
44	0.0	16.8	0.0	0.4	0.0	0.4	27.3	5.5	11.7	34.0	3.9
45	0.0	28.5	5.9	0.0	0.0	2.3	17.6	25.0	16.8	2.3	1.6
46	0.0	8.6	0.0	0.0	0.0	5.5	32.8	14.1	9.4	24.6	5.1
47	0.0	22.3	6.6	0.0	35.9	2.7	22.7	0.0	5.9	3.9	0.0
48	2.7	37.9	2.7	0.0	1.2	2.7	10.2	14.8	17.6	6.6	3.5
49	0.0	15.2	3.5	0.0	0.4	2.7	30.5	27.7	18.8	0.8	0.4
50	0.8	36.6	15.4	0.0	0.0	1.6	7.3	21.1	8.9	4.1	4.1
51	3.5	0.8	3.9	0.0	26.2	12.5	31.3	3.9	15.6	2.3	0.0
52	0.0	15.2	3.1	0.0	25.0	0.4	31.6	4.3	17.2	3.1	0.0
53	0.0	21.9	0.0	0.0	0.0	1.2	29.7	5.9	23.0	14.1	4.3
54	0.8	12.5	20.3	0.0	0.0	1.6	27.0	27.0	9.8	0.4	0.8
55	9.0	17.2	0.4	0.0	13.7	5.5	30.5	7.0	14.5	2.0	0.4
56	10.5	0.4	0.4	0.0	32.4	19.5	25.8	1.2	9.4	0.4	0.0
57	0.0	24.6	0.8	0.0	0.0	0.0	18.4	11.3	9.8	26.6	8.6
58	0.0	40.2	2.7	0.0	0.0	0.0	15.2	5.1	3.5	33.2	0.0
59	0.0	30.8	4.3	0.0	0.5	0.0	38.9	4.8	14.9	4.3	1.4
60	0.4	1.6	5.5	0.0	0.0	0.0	69.1	2.7	18.4	2.0	0.4
61	0.4	16.8	3.1	5.9	0.4	0.0	27.0	2.7	14.5	26.6	2.7
62	0.0	34.8	8.2	2.3	0.0	0.0	14.8	6.6	6.3	26.2	0.8
63	0.0	16.4	5.5	0.8	17.2	0.0	35.9	3.5	19.1	0.4	1.2
64	0.4	23.0	3.9	0.0	0.4	0.8	21.9	12.5	27.3	7.4	2.3
65	0.8	29.3	2.0	0.0	0.0	0.0	52.7	7.0	6.3	0.4	1.6

Table 3.4 Training area cover data collected in 1998

Training Area #	Bare silt crust	Stones	Organic crust	Lichens	Soft grasses	Annuals	Shrubs >35cm	Shrubs <35cm	Litter	Clump grasses >35 cm	Clump grasses >35 cm
66	5.0	40.0	2.0	1.0	3.0	3.0	35.0	4.0	6.0	0.0	1.0
67	2.0	5.0	2.0	2.0	1.0	6.0	61.0	9.0	8.0	3.0	1.0
68	5.0	1.0	2.0	1.0	5.0	8.0	63.0	5.0	9.0	0.0	1.0
69	2.0	10.0	7.0	2.0	0.0	1.0	60.0	10.0	7.0	0.0	1.0
70	4.0	40.0	8.0	1.0	10.0	3.0	5.0	8.0	7.0	13.0	1.0
71	35.0	20.0	10.0	1.0	0.0	5.0	8.0	5.0	8.0	7.0	1.0
72	0.0	0.0	0.0	0.0	12.0	16.0	50.0	2.0	20.0	0.0	0.0
73	5.0	20.0	13.0	2.0	7.0	10.0	20.0	5.0	22.0	0.0	1.0
74	30.0	15.0	25.0	0.0	2.0	2.0	6.0	15.0	5.0	2.0	1.0
75	3.0	8.0	6.0	1.0	2.0	8.0	20.0	18.0	20.0	10.0	3.0
76	5.0	0.0	1.0	0.0	12.0	30.0	35.0	7.0	10.0	1.0	0.0
77	10.0	45.0	30.0	1.0	1.0	2.0	12.0	4.0	3.0	0.0	2.0
78	5.0	0.0	0.0	0.0	8.0	35.0	3.0	2.0	20.0	28.0	0.0
79	3.0	0.0	1.0	0.0	3.0	10.0	40.0	2.0	15.0	26.0	0.0
80	21.0	3.0	10.0	1.0	10.0	15.0	0.0	4.0	18.0	18.0	0.0
81	3.0	20.0	2.0	2.0	20.0	15.0	2.0	16.0	10.0	10.0	0.0
82	10.0	35.0	15.0	8.0	1.0	2.0	6.0	2.0	6.0	15.0	0.0
83	1.0	0.0	0.0	0.0	0.0	6.0	70.0	2.0	15.0	8.0	0.0
84	6.0	5.0	14.0	5.0	2.0	2.0	17.0	5.0	20.0	20.0	4.0
85	0.0	5.0	0.0	0.0	5.0	20.0	35.0	15.0	20.0	0.0	0.0
86	5.0	30.0	10.0	4.0	2.0	6.0	20.0	15.0	6.0	3.0	1.0
87	4.0	15.0	2.0	1.0	0.0	3.0	35.0	15.0	3.0	20.0	2.0
88	5.0	41.0	5.0	1.0	0.0	1.0	2.0	1.0	10.0	35.0	0.0
89	0.0	2.0	0.0	1.0	0.0	4.0	60.0	6.0	22.0	5.0	0.0
90	8.0	5.0	5.0	1.0	2.0	30.0	30.0	10.0	9.0	0.0	0.0
91	5.0	30.0	10.0	0.0	0.0	5.0	10.0	5.0	5.0	30.0	0.0
92	3.0	56.0	10.0	0.0	0.0	10.0	1.0	10.0	5.0	10.0	2.0
93	10.0	20.0	5.0	1.0	0.0	3.0	0.0	5.0	5.0	50.0	0.0
94	15.0	22.0	5.0	0.0	1.0	1.0	5.0	40.0	7.0	0.0	0.0
95	3.0	1.0	0.0	0.0	20.0	50.0	5.0	13.0	4.0	0.0	3.0
96	5.0	20.0	10.0	1.0	4.0	10.0	8.0	15.0	27.0	0.0	0.0
97	0.0	25.0	20.0	0.0	0.0	1.0	10.0	4.0	10.0	30.0	0.0
98	5.0	30.0	10.0	2.0	0.0	1.0	18.0	8.0	5.0	21.0	0.0
99	40.0	1.0	0.0	0.0	19.0	8.0	2.0	5.0	20.0	5.0	0.0
100	0.0	18.0	17.0	2.0	0.0	5.0	30.0	15.0	12.0	0.0	1.0
101	0.0	0.0	4.0	4.0	65.0	10.0	10.0	5.0	8.0	0.0	0.0
102	0.0	1.0	2.0	0.0	31.0	10.0	20.0	20.0	5.0	0.0	1.0
103	2.0	2.0	5.0	0.0	10.0	15.0	40.0	15.0	15.0	0.0	5.0
104	0.0	7.0	5.0	1.0	2.0	10.0	50.0	10.0	15.0	0.0	0.0
105	25.0	35.0	3.0	0.0	2.0	3.0	9.0	15.0	8.0	0.0	0.0
106	55.0	3.0	1.0	0.0	1.0	3.0	0.0	20.0	17.0	1.0	1.0
107	0.0	19.0	0.0	15.0	0.0	2.0	20.0	25.0	20.0	0.0	1.0
108	16.0	25.0	15.0	1.0	0.0	8.0	15.0	15.0	5.0	0.0	0.0
109	4.0	25.0	20.0	2.0	0.0	4.0	5.0	15.0	5.0	8.0	10.0
110	20.0	40.0	20.0	1.0	0.0	1.0	0.0	5.0	10.0	0.0	5.0

Table 3.5 Training area cover data collected in 2000

3.6 Analysis of cover data

TWINSPAN and DECORANA can be found as separate programs, however all analysis using the two programs was carried out using the VESPAN package (versions II and III, Malloch, 1994; 1999) which contains the DECORANA and TWINSPAN programs, together with routines to allow organisation and selection of data for input into these two programs. It is more common to use both these analysis packages to investigate species data, but, instead of using species names in the routines, cover type names were used and Braun-Blanquet cover data values for these cover types were used instead of species data. The cover data values were adapted to a Braun-Blanquet type cover scale and are as shown in Table 3.6.

Adapted Braun-Blanquet scale	Cover value
1	Less than 1% (Scattered individuals)
2	1-5%
3	6-25%
4	26-50%
5	51-75%
6	76-100%

Table 3.6 Adapted Braun-Blanquet scale used with cover data in TWINSPAN and DECORANA analyses

Cover data from 1997 and 1998 were analysed together using TWINSPAN and DECORANA as they were collected to provide ground-truth for the whole of the study area to aid later interpretation of the ATM data. The aims of the analyses were first to ascertain how the training areas would be grouped together and which were most alike, and second to discover which environmental variables were most closely associated with the distribution patterns of the cover types. The second aim was addressed by comparing the groupings of training areas in TWINSPAN and DECORANA with environmental data collected in the field.

3.6.1 Analysis of cover data using DECORANA

DECORANA was used to analyse the cover data from the 1997 and 1998 field work. Standard DECORANA input options were used in the analysis. The data were output in the form of a text table and the sample scores were imported into Microsoft Excel and from there into SPSS 9.0 to investigate the relationships between the axes and different environmental variables. The axes were plotted against each other as scattergraphs with the environmental variable scores plotted above the DECORANA points. Each axis has an eigenvalue. Eigenvalues indicate the relative contribution to the explanation of the total variation in the data (Kent and Coker, 1992) . The eigenvalues for the DECORANA axis are as follows

Axis 1	0.126	44% of total variation)
Axis 2	0.08889	30% of total variation
Axis 3	0.03944	14% of total variation
Axis 4	0.03284	11% of total variation

This shows that axis 1 has a large part to play in the explanation of the total variation in the data, axis 2 has a slightly lesser part to play in the explanation of the variation, and axes 3 and 4 have small parts to play in the data explanation. Figure 3.6 shows axis 1 and axis 2 with the relevant training area number above each point and Figure 3.7 shows axes 3 and 4 plotted against each other.

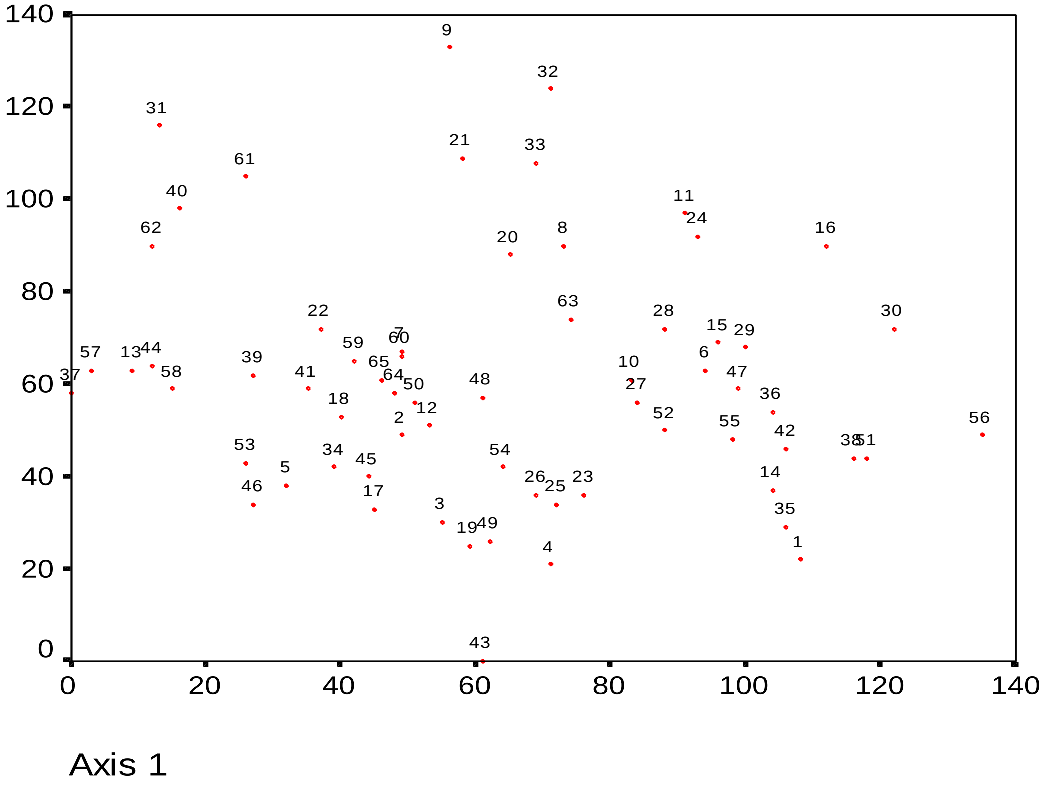


Figure 3.6 DECORANA axis 1 versus axis 2 showing training area numbers

In Figure 3.6 some separation of training areas into different groupings can be discerned, although not all of these groupings are particularly distinct. The separation indicates training areas with similar cover types. The investigation of the DECORANA results is to discover whether these groups of similar cover types appear to have any environmental relationships – for example whether they lie within the same geology type or have a similar slope or aspect. Figure 3.7 showing axes 3 and 4 had one training area removed (16) as it was an outlier causing the rest of the sites to bunch up in a corner of the graph. Even so, the sites plotted on this graph are clustered together in the centre showing little separation between the two axes. Plotting axes 3 and 4 against 1 and 2 also reveal a similar kind of clustering, reinforcing the limited contribution of axes 3 and 4 to the explanation of variation. Axes 1 and 2 are focused on in the next section, and the environmental datasets that were gathered in the field will be displayed with the DECORANA plots to investigate the factor that has the biggest part in the explanation of the training area data variation.

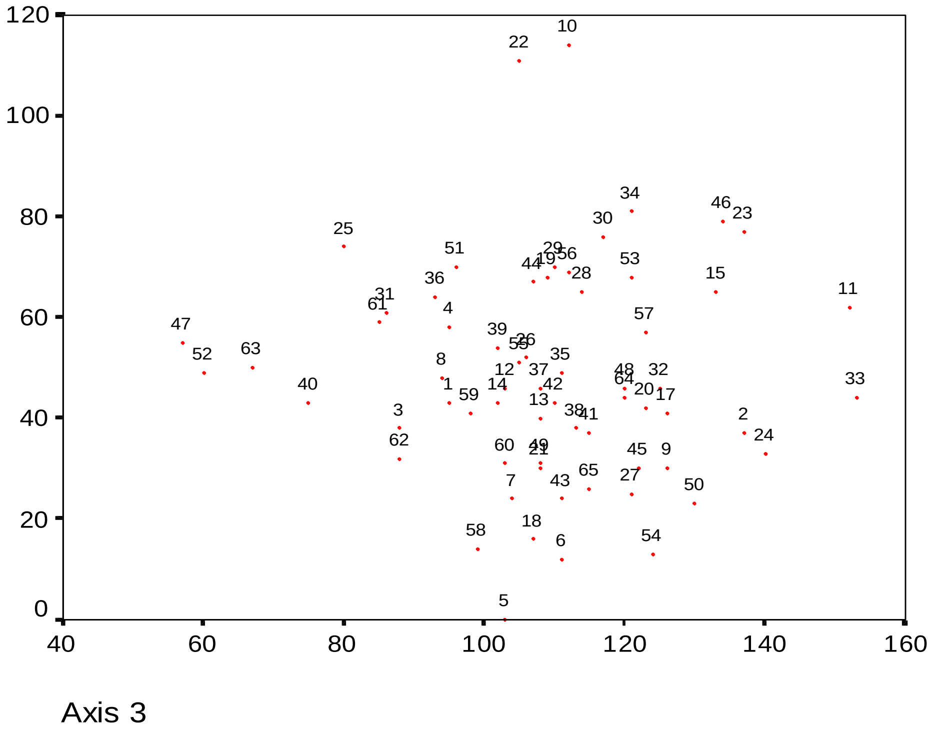


Figure 3.7 DECORANA axes 3 versus 4 showing training area numbers

3.6.1.1 DECORANA ordination and geology

DECORANA's first and second axes appear to offer some discrimination between geologies. Figure 3.8 shows MRU sites most often have lower axis 2 scores than TRU and Sorbas member sites. Sorbas sites are found to be along the first third of axis 1 having lower axis 1 scores than most MRU and TRU sites.

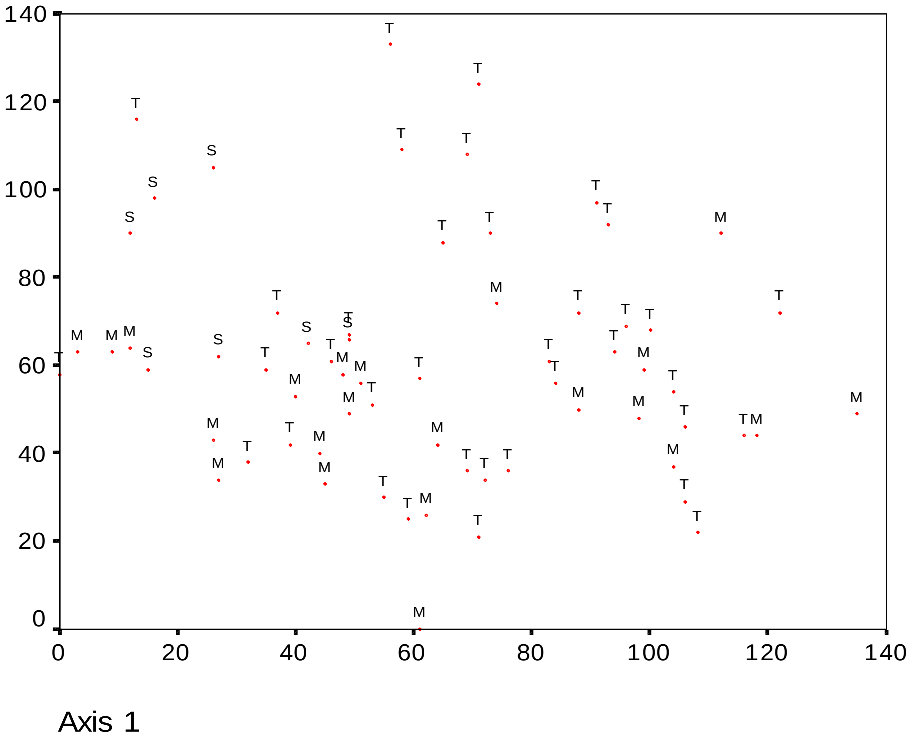
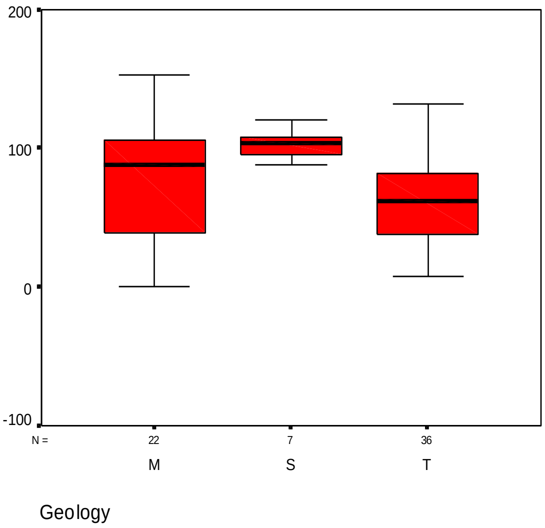


Figure 3.8 DECORANA axis 1 versus axis 2 showing geology (T= TRU, M=MRU, S=Sorbas)

Box plots of axes 1 and 2 with geology in Figure 3.9 (a and b) demonstrate the differences in scores for each of the geology types on both axes. Axis 1 shows a discrimination between Sorbas member geology and the two Gochar geology types and axis 2 shows the MRU and Sorbas member having much narrower ranges of DECORANA scores than the TRU with the Sorbas sites falling at top of the range of DECORANA scores and the MRU sites at the bottom. None of the geology types appears to have any association with axes 3 and 4.



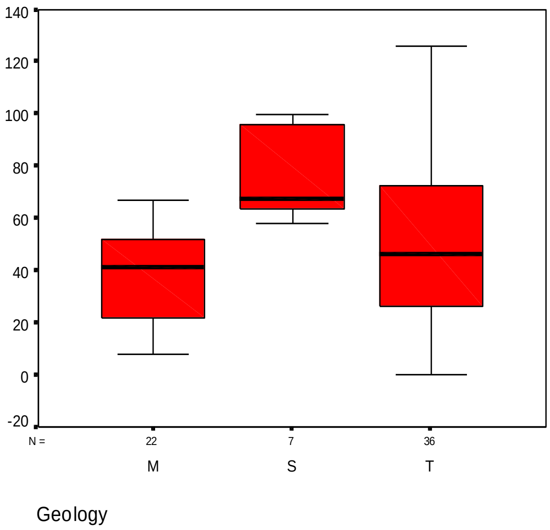


Figure 3.9 a) Axis 1 DECORANA scores and geology boxplot b) Axis 2 DECORANA scores and geology boxplot

3.6.1.2 DEOCRANA ordination and catchment

The DECORANA axes were tested to see if there was an association between cover and the catchment that the training area was surveyed in. A Mann-Whitney U test was carried out and the results for all axes had very low significances, the highest being that of DECORANA axis 1 with catchment with a P value of 0.09.

3.6.1.3 DECORANA ordination and aspect

Figure 3.10 shows the DECORANA axes 1 and 2 versus aspect. Aspect is grouped into 45º segments (1=339-23°, 2 =24-68°, 3 =294-338°, 4 =69-114°, 5 =249-293°, 6 =15-158°, 7 =204-248°, 8 =159-203°). The numbers 1-8 represent the eight directions with 1 being north and 8 south. This arrangement enables the aspect statistics for each training area to be correlated with DECORANA score as the higher the number, the closer to south. A two-tailed Spearman's rank correlation was carried out between aspect and all four axes and a significant correlation between axis 2 and aspect was found (p<0.319, which is significant at the 0.01 level). None of the other axes were significantly correlated with aspect. This correlation indicates quite a strong association between aspect axis 2.

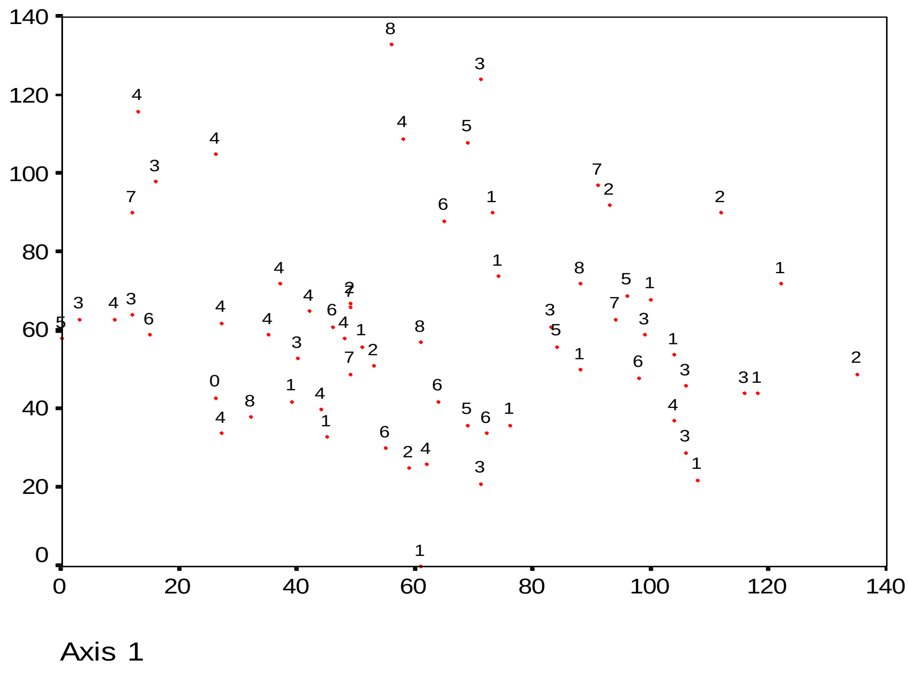


Figure 3.10 DECORANA axis 1 versus axis 2 showing aspect (1=339-23° 2 =24-68° 3 =294-338° 4 =69-114° 5 =249-293° 6 =15-158 ° 7 =204-248° 8 =159-203°)

3.6.1.4 DECORANA ordination and slope

Figure 3.11 shows slope as plotted on the DECORANA axes. There is not a particularly clear pattern associated with the axes, although it does appear that axis 1 discriminates somewhat between flat or low slope areas (0-5°) and steeper areas which mostly appear at the higher end of the axis.

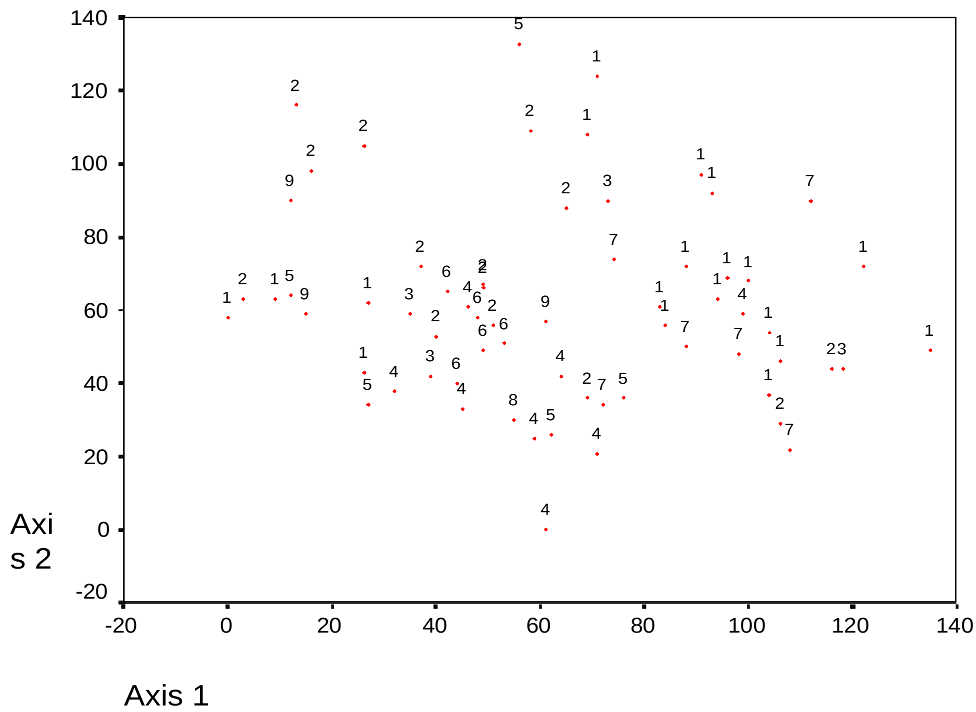


Figure 3.11 DECORANA axis 1 versus axis 2 showing slope (1=0-5° 2=6-10° 3=11-15° 4=16-20° 5=21-25° 6=26-30° 7=31-35° 8=36-40° 9=41-45°)

In general the steeper slopes are found in the cluster of training areas in the centre of the graph. Slope was correlated with all four DECORANA axes scores using a two-tailed Spearman's rank correlation. A significant correlation was found between axis 1 and slope ($p<0.276$ which is significant at the 0.05 level) indicating an association between slope and cover.

3.6.1.5 DECORANA ordination and soil chemistry

Limited chemical analyses were carried out on soil samples collected from the training areas. The tests undertaken were conductivity and cation analyses. These soil analyses and their results are reported in Appendix 2. Soil was not collected from all training areas (in some cases there was no soil, only a calcrete crust with plants growing from cracks in the crust) leaving an incomplete dataset. Soil analyses results were correlated with all DECORANA axes and there are some strong correlations between the soil data and DECORANA scores. These are shown in Table 3.7.

Soil test	Axis	Spearman's rank score	Level of significance
Conductivity (soil)	Axis 2	.411	0.01
Potassium (soil)	Axis 1	-.321	0.05
Potassium (crust)	Axis 3	.341	0.05
	Axis 4	.394	0.05
Sodium (soil)	Axis 1	-.317	0.05
	Axis 2	.424	0.01
Calcium (soil)	Axis 1	.434	0.01
Magnesium (crust)	Axis 1	-.376	0.05

Table 3.7 Spearman's rank correlation scores and levels of significance for soil chemistry and DECORANA axes

There are some obvious associations between various cations and all four of the DECORANA axes. There are strong associations between axis 2, and sodium ions and conductivity (conductivity being related to the levels of cations in the soil, particularly sodium (Hesse, 1971)). There are also negative associations between axis 1 and potassium, sodium and magnesium ions and a positive association between this axis and calcium indicating that certain cover types are found where there are high levels of calcium and low levels of other exchangeable ions. Axes 3 and 4 have a positive correlation with potassium ions, none of the other ions appear to be related to these axes.

3.6.1.6 Summary of DECORANA cover results

Soil chemistry appears to have a strong association with the distribution of the training area cover data along axes 1 and 2 (and to a lesser extent with axes 3 and 4). The distribution of training areas along axis 1 has an association with slope with discrimination between shallow angle slopes and much steeper angle slopes. Axis 2 has a strong correlation with aspect indicating that aspect is associated with the distribution of training areas. Geology has less of an association with training area distribution, and the boxplots in Figure 3.9 indicate that TRU sites can be found along the length of both axes 1 and 2. MRU has a very similar distribution to TRU on axis 1, but there is more discrimination on axis 2 where this geology type is found at the bottom of the DECORANA axis and the Sorbas geology is found at the top. The distribution of Sorbas geology sites are associated with both axes 1 and 2. There is no significant relationship between DECORANA axes and catchment.

3.6.2 DECORANA analysis of floristic data

DECORANA was used to analyse the species data collected in the field in 1997 and 1998. Standard DECORANA input options were used in the analysis . The results were output in the form of a text table and the sample scores were imported into Microsoft Excel and from there into SPSS 9.0 to investigate the relationships between the axes and environmental variables. Axis pairs were plotted as scattergraphs with the environmental variable scores plotted above the DECORANA points. Correlation of DECORANA axes and environmental variable were carried out where appropriate. Where this was not possible, boxplots were used instead

The eigenvalues for the DECORANA species analysis axis are as follows

Axis 1	0.42308	42% of total variation
Axis 2	0.23718	23% of total variation
Axis 3	0.19862	20% of total variation
Axis 4	0.15287	15% of total variation

This shows that axis 1 has the largest contribution to the variation in training area distribution. Comparing the percentage contribution of the axes to the explanation for the variation it can be seen that axes 2 and 3 have a similar level of importance.

The distribution of training areas on axes 1 and 2 are shown in Figure 3.12 and on axes 3 and 4 in Figure 3.13

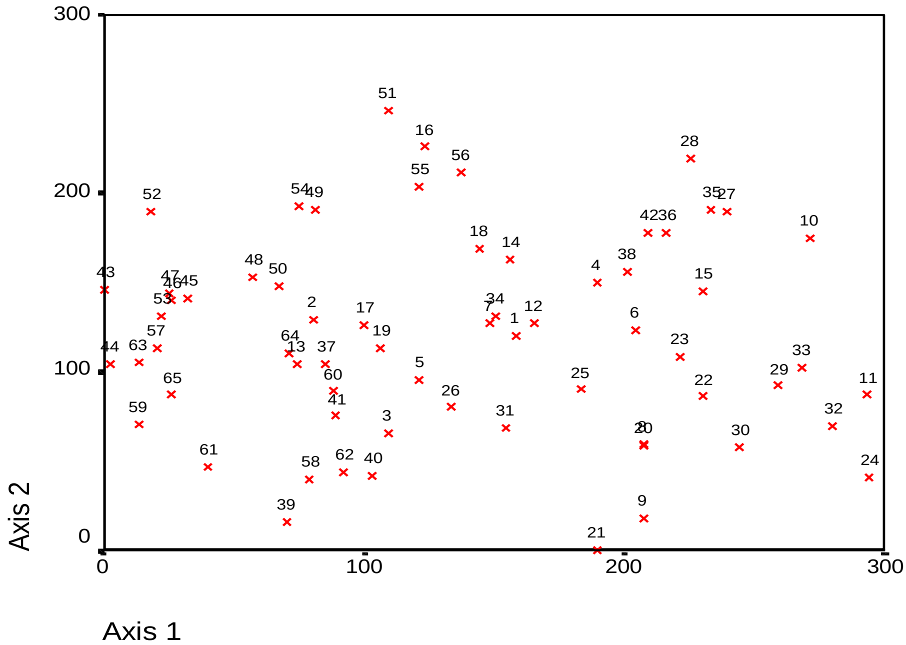


Figure 3.12 DECORANA axes 1 and 2 with training area numbers

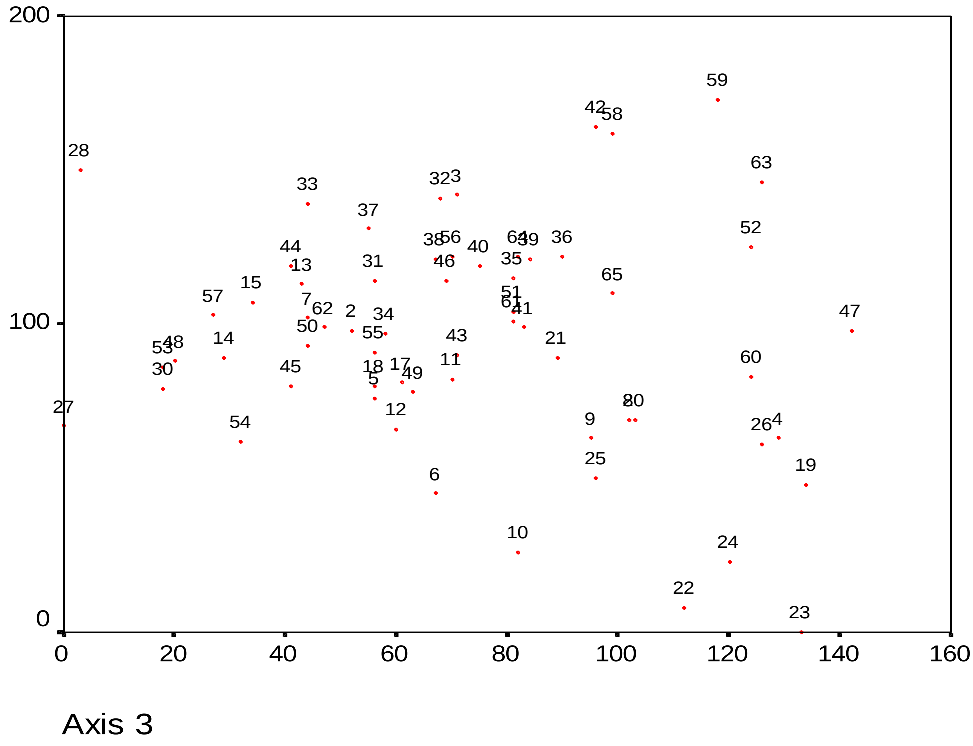


Figure 3.13 DECORANA axes 3 and 4 plotted with outliers 1, 16 and 29 removed

Neither of the graphs displays distinct groupings of training areas indicating a more continuous variation than was the case for the cover data (Figure 3.2).

3.6.2.1 Floristic DECORANA axes and geology

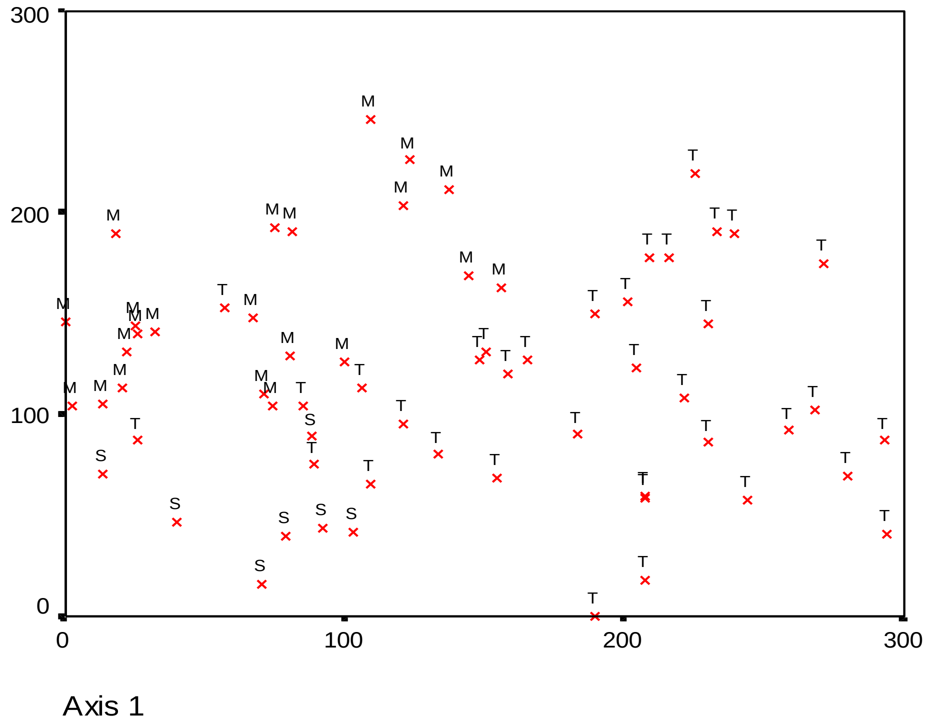
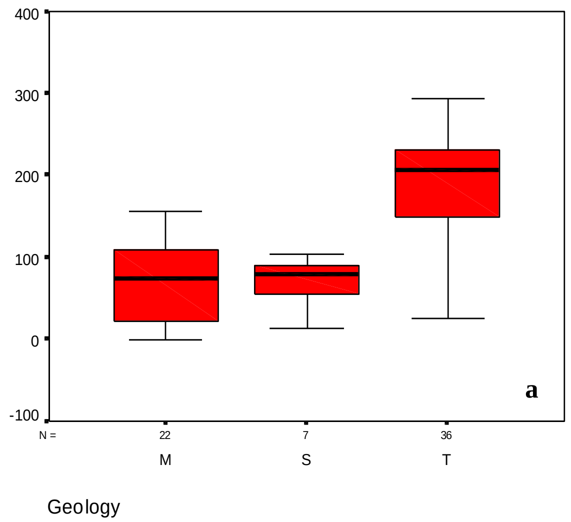


Figure 3.14 Axes 1 and 2 plotted with geology

A relationship between geology and both axes 1 and 2 is shown in Figure 3.14. Axis 1 discriminates between sites on Sorbas member and MRU geology which are at the lower end of the axis from sites on TRU geology. Axis 2 separates sites on MRU (high scores) from those on the Sorbas member. However, TRU sites are found across the range of DECORANA scores. This is shown more clearly in the boxplots in Figure 3.15 where axis 1 shows a low score association with MRU and Sorbas geology, and TRU associated with higher DECORANA scores. Axis 2 shows MRU with a high DECORANA score association, Sorbas member sites with a low, narrow range and TRU spread across the range of DECORANA scores.



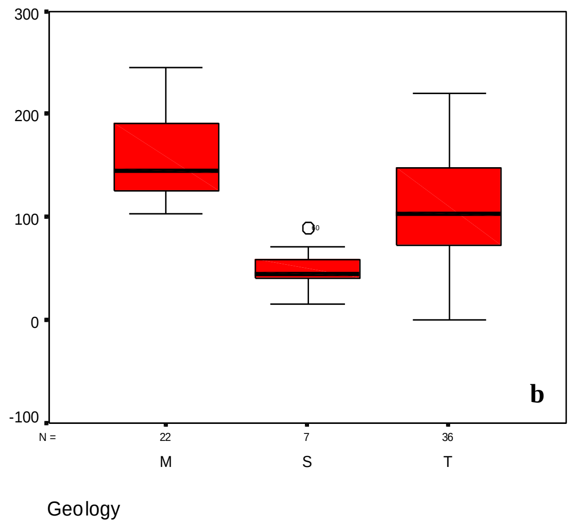


Figure 3.15 a) Axis 1 floristic DECORANA scores and geology boxplot b) Axis 2 floristic DECORANA scores and geology boxplot

3.6.2.2 Floristic DECORANA axes and catchment

There appears to be a strong association between axis 1 and the catchment in which the training areas are situated. The DECORANA plot discriminates between the two catchments with Infierno sites appearing at the low end of axis 1 and Mocatán sites found at the high end of axis 1 with some intermixing in the centre of the axis (Figure 3.16). A Mann-Whitney U test was performed on the DECORANA axes to see if there was a significant relationship between catchment and DECORANA score. The results from the test indicated a very high significance for axis 1 (the SPSS Mann-Whitney test gives it an asymptotic significance of $p<0.000$). Axis 2 is also significantly associated with catchment at the 0.05 level (asymptotic significance $p<0.051$). Although 'catchment' is obviously not an environmental variable itself, it can be used as an analogue for differences in the landscape caused by the different erosional histories of the Infierno and Mocatán catchments. The fact that there are very strong associations between species distribution and catchment indicates that the loss of sediment from the Infierno catchment by river-capture induced erosion may be a factor in the distribution of species across the study area.

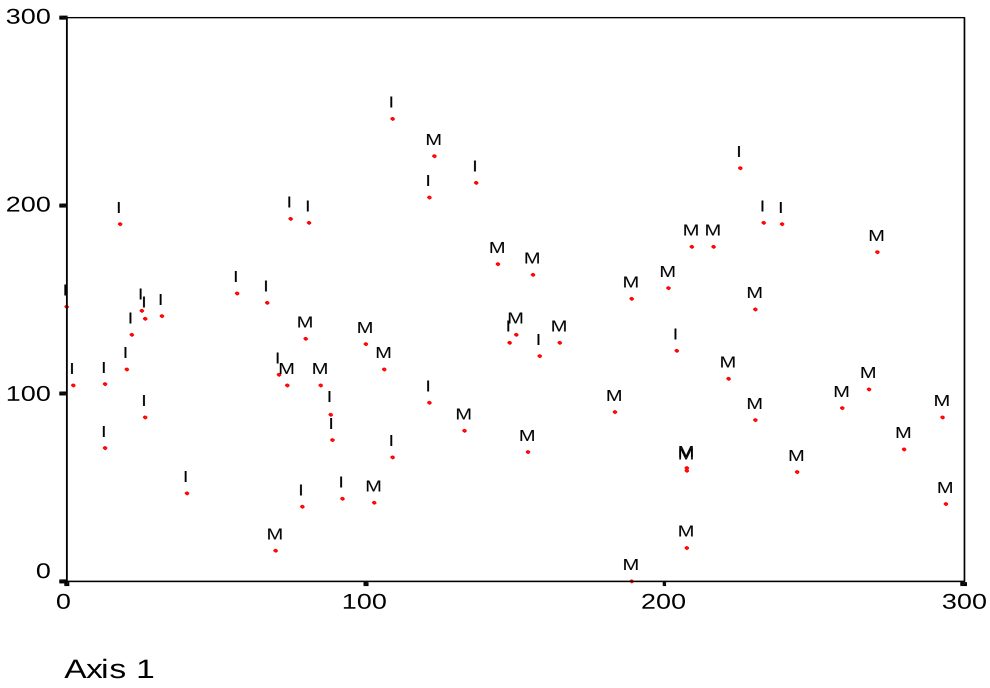


Figure 3.16 Floristic DECORANA axes 1 and 2 plotted with collection catchment (I=Infierno M=Mocatán)

3.6.2.3 Floristic DECORANA ordination and aspect

Figure 3.17 shows axes 1 and 2 plotted with aspect. There does not appear to be much association between aspect and species distribution. This statement is supported by the fact that there is no significant correlation between aspect and DECORANA axes. None of the Spearman's rank correlations for aspect and the four axes is more significant than $p<0.23$.

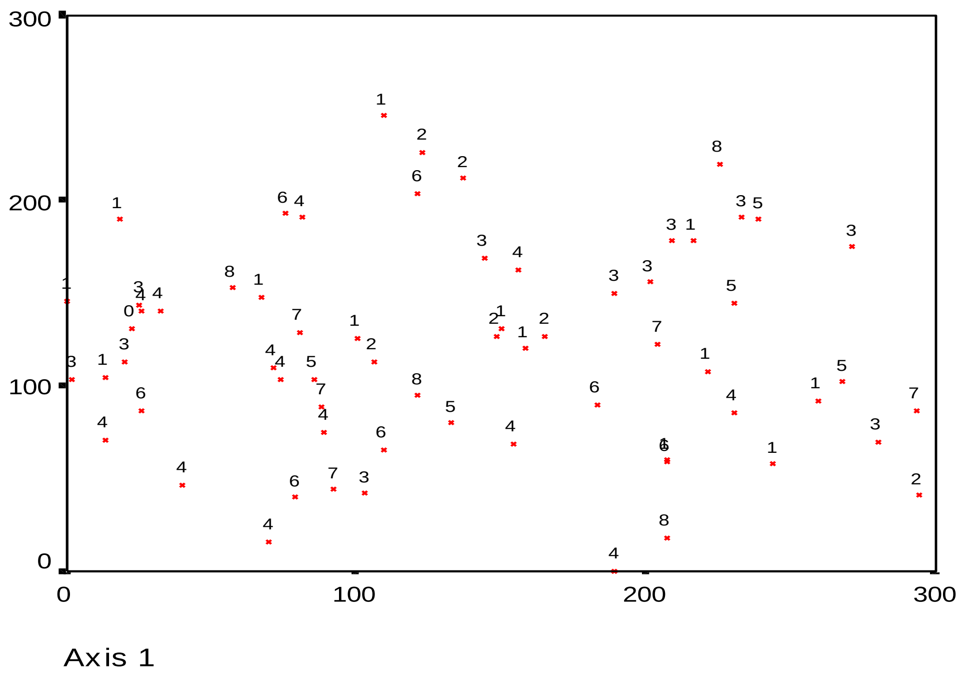


Figure 3.17 Floristic DECORANA axes 1 and 2 plotted with aspect (1=339-23° 2 =24-68 3 =294-338° 4 =69-114°5 =249-293° ° 6 =15-158 ° 7 =204-248° 8 =159-203°)

3.6.2.4 Floristic DECORANA ordination and slope

Figure 3.18 shows the scattergraph of DECORANA floristic axes 1 and 2 plotted with slope. There appears to be an association between axis 1 and slope. A high axis 1 score indicates to some extent a low slope value and lower axis 1 scores indicates steeper slopes. This association is supported by a Spearman's rank correlation score of -0.496 which is significant at the 0.01 level. However there is no association between slope and axes 2, 3 and 4.

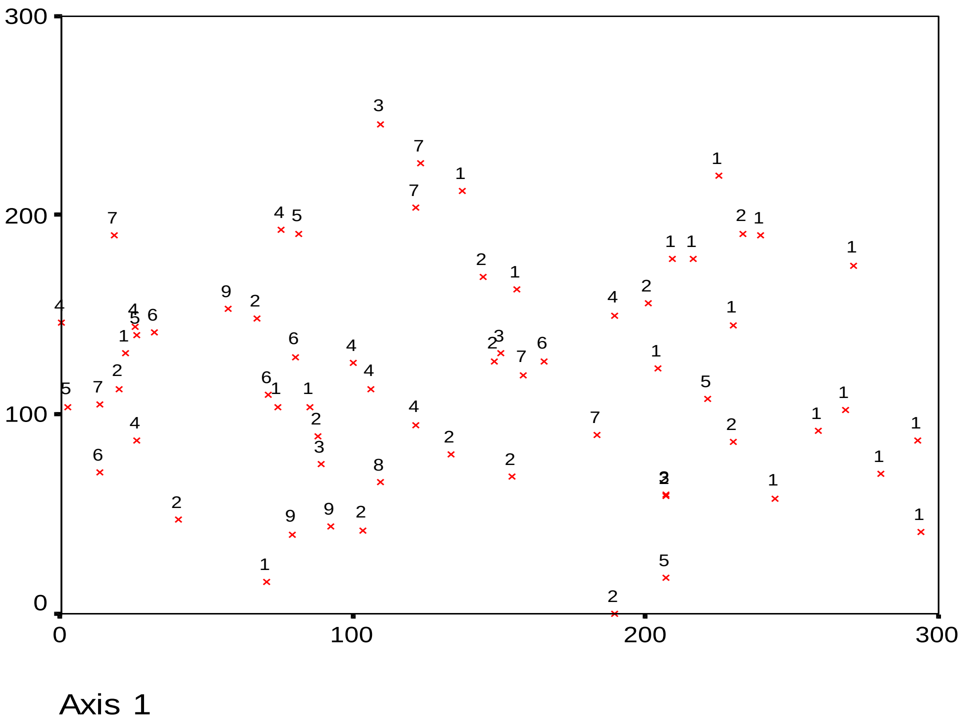


Figure 3.18 DECORANA axis 1 versus axis 2 showing slope (1=0-5° 2=6-10° 3=11-15° 4=16-20° 5=21-25° 6=26-30° 7=31-35° 8=36-40° 9=41-45°)

3.6.2.5 Floristic DECORANA axes and soil chemistry

Soil analysis results were correlated with all DECORANA axes and there are some significant correlations between the soil data and DECORANA scores. These are shown in Table 3.8. Axis 1 is significantly positively correlated with conductivity (soil), potassium (soil) sodium (crust and soil) and magnesium (crust). Axis 1 is negatively correlated with calcium (soil and crust). This indicates a strong association between species distribution and soil chemistry with training areas at the bottom end of axis 1 having low sodium, potassium and magnesium levels, and high calcium levels. Axis 2 has weak negative correlations with conductivity (soil and crust) and sodium (crust). Axis 3 is correlated with conductivity (crust) and potassium (crust). Axis 4 has no association with soil chemistry.

These correlations indicate that species are sensitive to soil chemistry, more so than cover is. It indicates that distribution of species is highly likely to be associated with soil chemistry with some plants preferring soils with high calcium and low sodium, potassium and magnesium levels.

Soil test	Axis	Spearman's rank score	Level of significance
Conductivity (soil)	Axis 1	.304	0.05
	Axis 2	-.364	0.05
Conductivity (crust)	Axis 2	-.384	0.05
	Axis 3	.440	0.01
Potassium (soil)	Axis 1	.404	0.01
Potassium (crust)	Axis 3	.344	0.05
Sodium (soil)	Axis 1	.461	0.01
Sodium (crust)	Axis 1	.403	0.01
	Axis 2	-.313	0.05
Calcium (soil)	Axis 1	-.455	0.01
Calcium (crust)	Axis 1	-.400	0.01
Magnesium (crust)	Axis 1	.361	0.05

Table 3.8 Spearman's rank correlation scores and levels of significance for soil chemistry and floristic DECORANA axes

3.6.2.6 Floristic DECORANA summary

The distribution of plant species in the study area appears to show some relationship to the measured environmental variables. The strongest relationship with distribution is that of catchment. The relationship here is one of species with the different catchment geomorphological histories, where one catchment has been eroded and stabilised and the other is currently eroding. This leads to questions about the environmental variables which give the two catchments different species distributions, such as geology, soil depth and soil moisture. Unfortunately this analysis is beyond the scope of the thesis and remains a question that needs to be answered. Soil chemistry is another environmental variable which is highly related to distribution of species in the field area with some strong positive correlations between various cations and axis 1. Geology is less strongly related to distribution of species indicating that geology may not be the driving factor for species distribution between the two catchments as all three geology types are found in both catchments. There is a relationship between axis 1 and slope, but there is no obvious association between aspect and species distribution.

3.6.3 TWINSPAN analysis of cover data

TWINSPAN was run three times using the cover data with different input variables such as the number of cutlevels and pseudospecies cutlevels. The output file of the TWINSPAN run used, 'TwinoutC', is reported below as this produced the most coherent cover groups. The input variables were defined as follows: samples to be omitted (none), pseudospecies cut levels (3 at 0.1 2.1 4.1), minimum size for group division (6), maximum number of indicator species (4), maximum number of species in final table (default), maximum level of divisions (5), pseudospecies weights (default – all the same weight), indicator potentials for cut levels (default), no species omitted.

The output of TwinoutC.lis was plotted in a tree diagram to enable final groupings of training areas to be identified. This tree diagram is shown in figure 3.19. As can be seen the initial cut at level 1 makes a fairly even division of training areas based on the low occurrence of grasses and annuals on the positive side and medium levels of stone cover on the negative side.

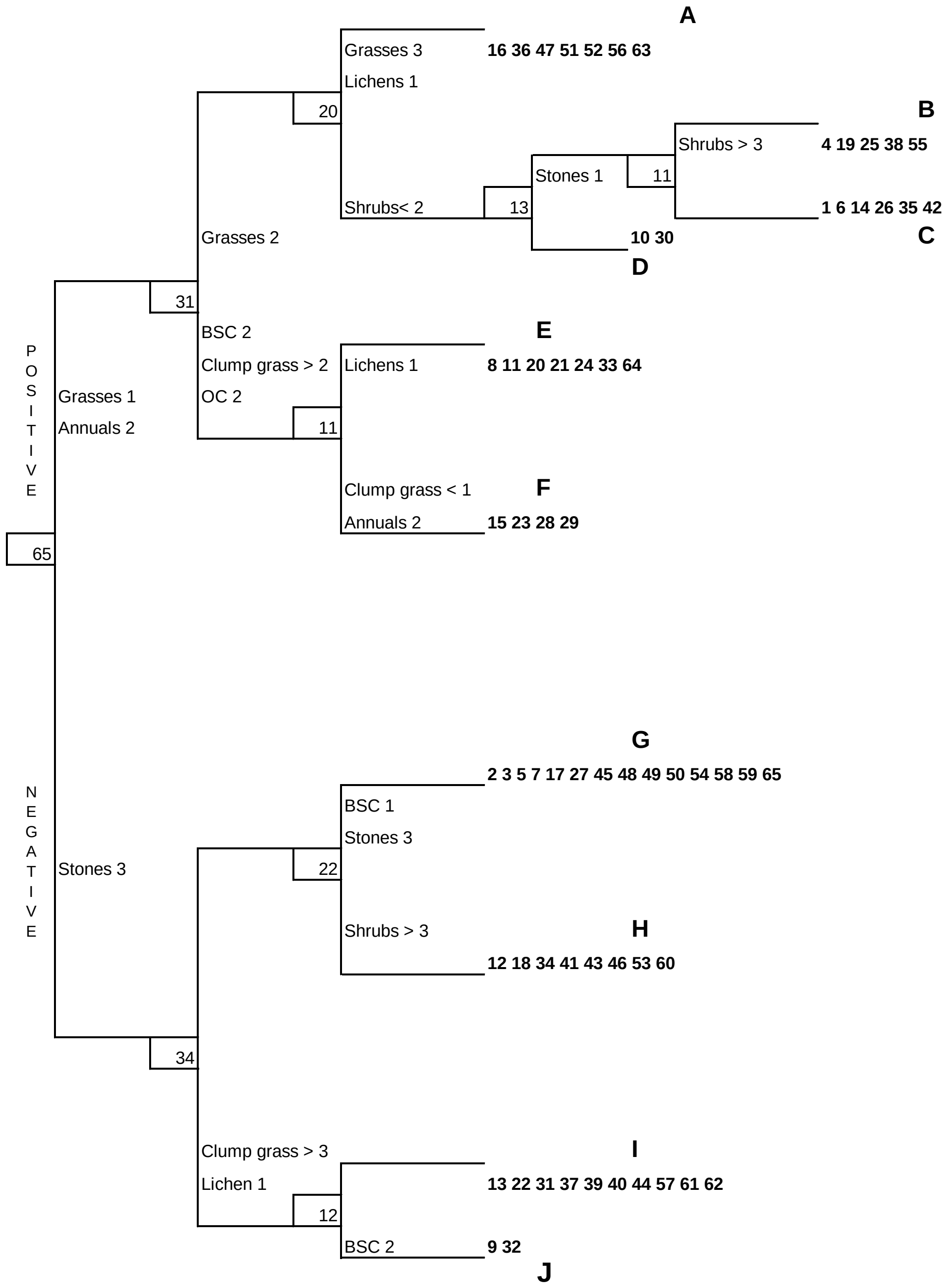


Figure 3.19 TWINSPAN tree diagram showing cut species and end groups of training areas

Field investigation was carried out to verify that the training areas which had been grouped together by TWINSPAN were actually similar in composition. All cover TWINgroups as shown in Figure 3.19 are defined in Table 3.9.

	Group	Training areas in group	Description of cover from field observation
Positive	**A**	16, 36, 47, 51, 52, 56, 63	Dense and shrubby with stone cover, soft grasses and annuals
	B	4, 19, 25, 38, 55	Dense shrubby vegetation cover with annuals and soft grasses. No *Stipa tenacissima*.
	C	1, 6, 14, 26, 35, 42	These training areas have a moderate cover of large shrubs with quite high cover of litter, no clump grass and with organic crust on the bare ground.
	D	10 30	These training areas are both found in terraces which have a high proportion of dying vegetation.
	E	8, 11, 20, 21, 24, 33, 64	These are sites with a high proportion of bare silt crust.
Negative	**F**	15, 23, 28. 29.	The training areas in this group do not have much in common cover-wise, however three of the four are in agricultural terraces.
	G	2, 3, 5, 7, 17, 27, 45, 48, 49, 50, 54, 58, 59, 65	Sparse, mainly clumped vegetation, stony ground cover found mainly on hillsides.
	H	12 18 34 41 43 46, 53, 60	Dense shrub cover with stones. No soft grass lower. Most often found on ridgetops.
	I	13, 22, 31, 37, 39, 40, 44, 57, 61, 62	Generally *Stipa tenacissima* tussock covered and stone armoured.
	J	9, 32	Mainly silt wash cover, sparsely vegetated few stones, both sites in the Mocatán catchment. Not many such as this sampled as most have no vegetation

Table 3.9 TWINSPAN cover groups with descriptions of cover types

Training area TWINgroups were crosstabulated with geology and catchment (Tables 3.10 and 3.11). There is some separation of sites by geology in some of the TWINgroups. Training areas on TRU geology separate out in groups D, F and J where they are found without training areas on other geology types. Groups B, C and E all have only one training area on MRU with the rest being found on TRU.

		Geology		Total
Twingroup	**MRU**	**Sorbas**	**TRU**	
A	6		1	7
B	1		4	5
C	1		5	6
D			2	2
E	1		6	7
F			4	4
G	6	2	6	14
H	4	1	3	8
I	3	4	3	10
J			2	2
Total	22	7	36	65

Table 3.10 Training areas crosstab table of TWINgroup and geology

Training areas on MRU geology separated out in group A where all but one training area was found on this geology type. Training areas on Sorbas geology were not as well separated, but were found in groups G, H and I (these groups all separated out on the negative side of the TWINSPAN split). There is some separation of TWINgroups by catchment. Members of groups D and J occur exclusively in the Mocatán catchment and groups B, E and F show a high proportion of Mocatán sites. Groups A and G are dominated by Infierno catchment sites. There was obviously some element of separation by catchment by TWINSPAN

	Catchment		
Twingroup	**Infierno**	**Mocatán**	Total
A	5	2	7
B	1	4	5
C	3	3	6
D		2	2
E	1	6	7
F	1	3	4
G	12	2	14
H	5	3	8
I	4	6	10
J		2	2
Total	32	33	65

Table 3.11 Training areas crosstab table TWINgroup and catchment

Crosstabulation of TWINgroup and aspect is shown in Table 3.12. TWINgroup A contains training areas with northerly aspects (294°-68°). TWINgroup H mostly has training areas between 338° and 114°. This could be associated with the fact that many of these sites are found on north-west trending ridgetops in the Infierno catchment. Training areas in TWINgroup 4 appear to have some relationship with aspect as 10 out of 14 are found with a trend towards the south-east. These aspects may also be associated with sparse vegetation cover in the training areas. None of the other TWINgroups appears to have a tight association with aspect.

	Aspect class									
Twingroup	**Flat**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**Total**
A		4	2	1						7
B			1	2			2			5
C		1		2	1	1		1		6
D		1		1						2
E		1	1		2	1	1	1		7
F		2				1			1	4
G		2	1		3	1	4	1	2	14
H	1	2	1	1	2			1		8
I				3	5	1		1		10
J				1					1	2
Total	1	13	6	11	13	5	7	5	4	65

Table 3.12 TWINgroup crosstabulated with aspect (1=339-23° 2=24-68° 3=294-338° 4=69-114° 5=249-293° 6=15-158 ° 7=204-248° 8=159-203°)

There is no apparent association between TWINSPAN group and slope. The classified slope scores are widely distributed for all TWINgroups and are not shown.

Using boxplots to display cover TWINgroup against soil sodium cation levels, it can be seen that TWINgroups E and J have the highest median sodium values (Figure 3.20a). These are both groups whose training areas are found to have mainly bare silt crust cover and sparse vegetation. Group C has a wider range of sodium values, but only one out of the four training areas for which sodium cation values were determined has a value over 100 mg/l. Figure 3.20b shows calcium cation levels by TWINgroup as boxplots. It can be seen that there is some variation in calcium levels by TWINSPAN group with groups I and J having the highest calcium levels. In TWINgroups E and J both sodium and calcium levels are high. Both these TWINSPAN groups have a high proportion of bare silt crust cover. Group E also has high values for magnesium ions (not shown). Group C also appears to have a wider range of sodium values, but only one of the four training areas for which sodium cation values were determined has a value over 100mg/l.

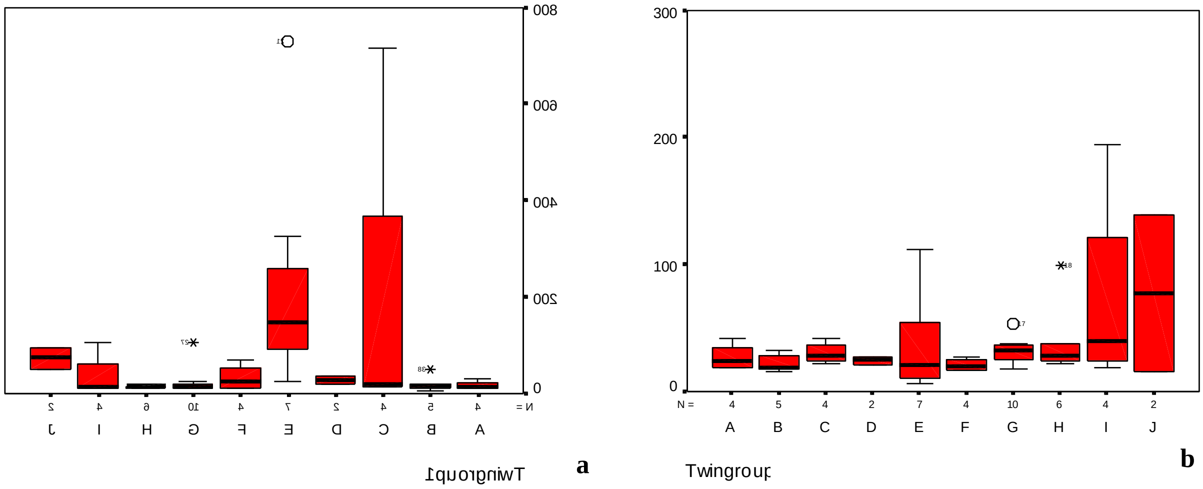


Figure 3.20 a) Boxplot of cover TWINgroup and sodium (mg/l) b) Boxplot of cover TWINgroup and calcium (mg/l)

3.6.3.1 Summary of the cover data TWINSPAN analysis

Cover TWINgroups are associated with geology and catchment. There is also some association of TWINSPAN group with aspect and sodium and magnesium cation levels. TWINSPAN mostly separated training areas of similar cover types into the same groups. However the similar cover types in the training areas did not necessarily have similar percentages of cover.

3.6.4 TWINSPAN analysis of floristic data

The output of the species TWINSPAN run, Speciesout.lis is reported in a tree diagram in Figure 3.21. The input variables were defined as follows: samples to be omitted (none), pseudospecies cut levels (3 at 0.1 2.1 4.1 using the same modified Braun-Blanquet scale see Table 3.6), Minimum size for group division (5), maximum number of indicator species (7) maximum level of divisions (4), pseudospecies weights (default – all the same weight), no species omitted. The 65 training areas were not divided as evenly as the cover data in the TwinoutC TWINSPAN run and there were 11 end groups after the four cut levels had been output. These TWINSPAN groups are defined in Table 3.13.

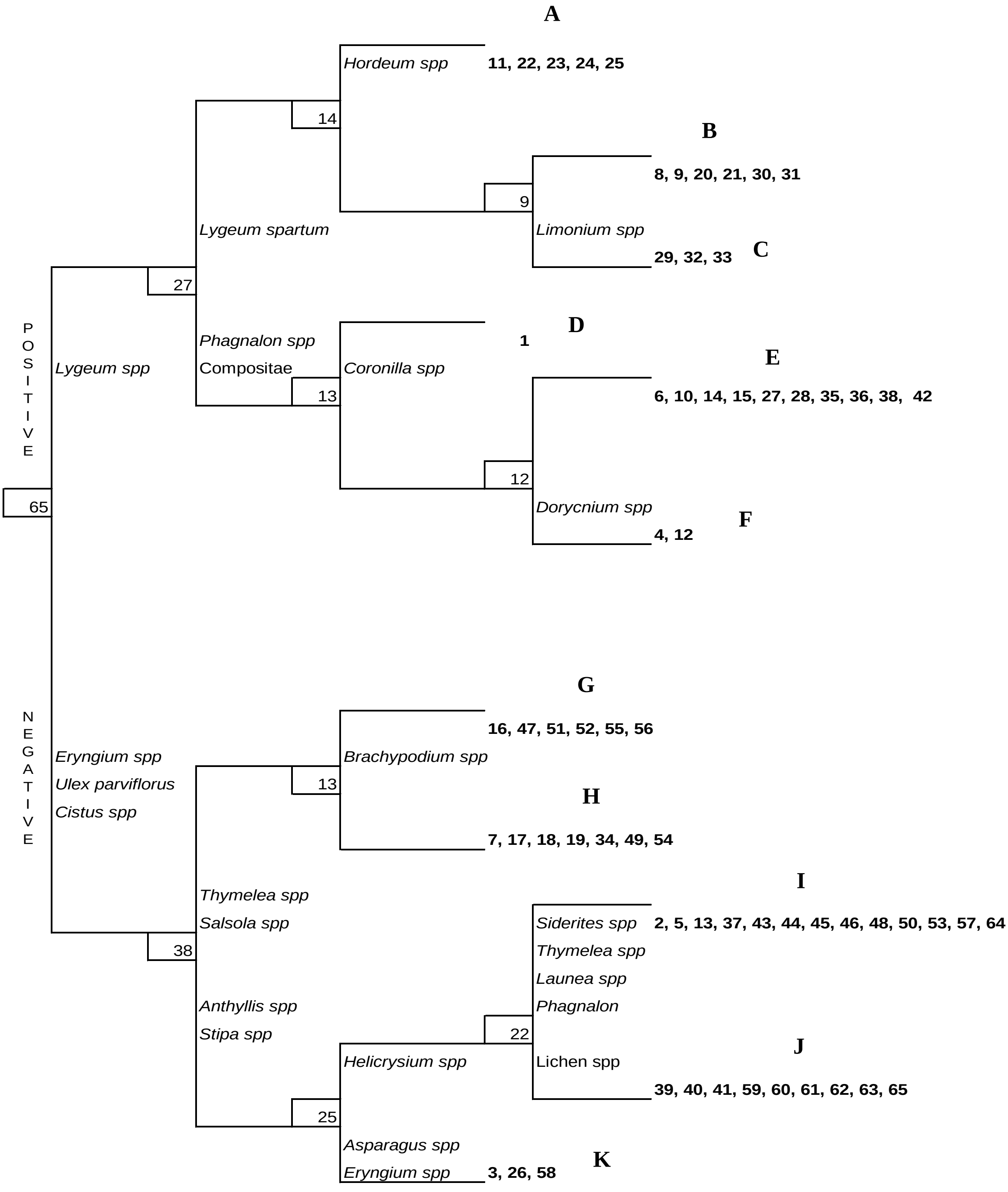


Figure 3.21 Species TWINSPAN tree diagram showing indicator species and end groups of training areas

	TWIN group	Training areas in group	Description
Positive	**A**	11, 22, 23, 24, 25	Characterised by *Anthyllis spp*, *Artemisia spp*, *Astragalus monspessulanus.*, *Hordeum spp.*, *Lygeum spartum* and *Thymus spp*. Mostly sparse to medium dense cover.
	B	8, 9, 20, 21, 30, 31	Characterised by *Anthyllis spp.*, *Artemisia spp.*, *Lygeum spartum, Salsola genistoides* and *Stipa tenacissima*. Mostly sparsely covered training areas.
	C	29, 32, 33	Characterised by *Anthyllis spp. Lathyrus spp.*, *Limonium insigne* and *Lygeum spartum*. These training areas have varied cover density.
	D	1	Characterised by *Anthyllis spp*., *Astragalus spp*., *.Brachypodium retusum* and *Coronilla spp*. High cover density.
	E	6, 10, 14, 15, 27,28, 35, 36, 38, 42	Training areas characterised by *Anthyllis spp*., *Compositae*, *Dactylis glomerata*, *Phagnalon spp*., and *Salsola genistoides*. Variety of cover densities.
	F	4, 12	Training areas have medium annuals cover, *Anthyllis spp*., *Dorycnium pentaphyllum*, *Phagnalon spp*., *Salsola genistoides* and *Thymelea spp*. Both training areas have dense vegetation cover.
Negative	**G**	16, 47, 51, 52, 55, 56	High cover of *Brachypodium retusum*. Other species found in most training areas include *Cistus spp*., *Helichrysum spp*, *Phagnalon spp*., *Salsola genistoides*, *Thymelea spp* and *Thymus spp*. Vegetation cover in these training areas is dense.
	H	7, 17, 18, 19, 34, 49, 54	Training areas in this TWINSPAN group are characterised by *Cistus spp*., *Fumana ericoides*, *Salsola genistoides Thymelea spp*., and *Thymus spp*. Vegetation cover is generally high in these training areas.
	I	2, 5, 13, 37, 43, 44, 45, 46, 48, 50, 53, 57, 64	These training areas are characterised by *Anthyllis spp*., *Cistus spp*., *Helianthumum spp*., *Launea spinosa*, *Stipa tenacissima* (which had very high cover values in all training areas) and *Thymelea spp*. Vegetation cover is generally medium dense, but not as dense as groups G and H.
	J	39, 40, 41, 59, 60, 61, 62, 63, 65	These training areas have high levels of *Cistus spp* cover and separation of this group was also characterised by the presence of lichen. *Stipa tenacissima* was found in all of these training areas. Cover was medium dense.
	K	3, 26, 58	This group is characterised by *Asparagus stipularis*, *Cistus spp*. and *Launea spinosa*. Vegetation cover is medium sparse in these training areas.

Table 3.13 TWINSPAN species groupings with descriptions of the main species found in these groupings

There is a very distinct separation of the TWINgroups with geology (Table 3.14). Training areas in TWINgroups A, B, C, D and F are found solely on TRU, and E has only one out of ten training areas on MRU, the rest being on TRU. TWINgroup G has training areas solely on MRU geology, and TWINgroups H and I have the majority of training areas on MRU. Group J has training areas mainly Sorbas geology and Group K has one training area on Sorbas and two on TRU.

Species TWINgroups	Geology M	S	T	Total
A			5	5
B			6	6
C			3	3
D			1	1
E	1		9	10
F			2	2
G	6			6
H	5		3	8
I	9		3	12
J	1	6	2	9
K		1	2	3
Total	22	7	36	65

Table 3.14 Species TWINgroups crosstabulated with geology

The TWINSPAN analysis of the species training area data shows a clear association with geology. The positive side of the TWINSPAN first level split contains only one training area on the MRU and none on the Sorbas member. Training areas on the MRU are mostly found on the positive side of the initial negative TWINSPAN split and training areas on the Sorbas member are found on the negative side of this negative split. Training areas on the TRU are found at low levels throughout the negative side of the TWINSPAN analysis.

Species TWINgroups	Catchment I	M	Total
A		5	5
B		6	6
C		3	3
D	1		1
E	4	6	10
F		2	2
G	5	1	6
H	4	4	8
I	9	3	12
J	7	2	9
K	2	1	3
Total	32	33	65

Table 3.15 Species TWINgroups crosstabulated with catchment

Separation of TWINgroups by catchment (Table 3.15) is not as clear as that by geology although groups A, B, C and F occur exclusively in the Mocatán catchment and the majority of TWINgroups I and J are in the Infierno catchment. This reflects more the geology of the catchments as the majority of training areas on the TRU are found in the Mocatán catchment and the majority of training areas on the MRU are in the Infierno catchment. Training areas on the Sorbas member can be found in both catchments.

There appears to be no obvious relationship between species TWINgroup and aspect, but there is a relationship between TWINgroups and slope. This is shown in Table 3.16.

Species TWINgroups	Slopeclass 1	2	3	4	5	6	7	8	9	Total
A	2	1			1		1			5
B	1	3	1		1					6
C	3									3
D							1			1
E	8	2								10
F				1		1				2
G	1		1	1			3			6
H		2	1	4	1					8
I	3	2		1	2	3			1	12
J	1	3	1	1		1	1		1	9
K		1						1	1	3
Total	19	14	4	8	5	5	6	1	3	65

Table 3.16 Species TWINgroup crosstabulated with slope (1=0-5° 2=6-10° 3=11-15° 4=16-20° 5=21-25° 6=26-30° 7=31-35° 8=36-40° 9=41-45°)

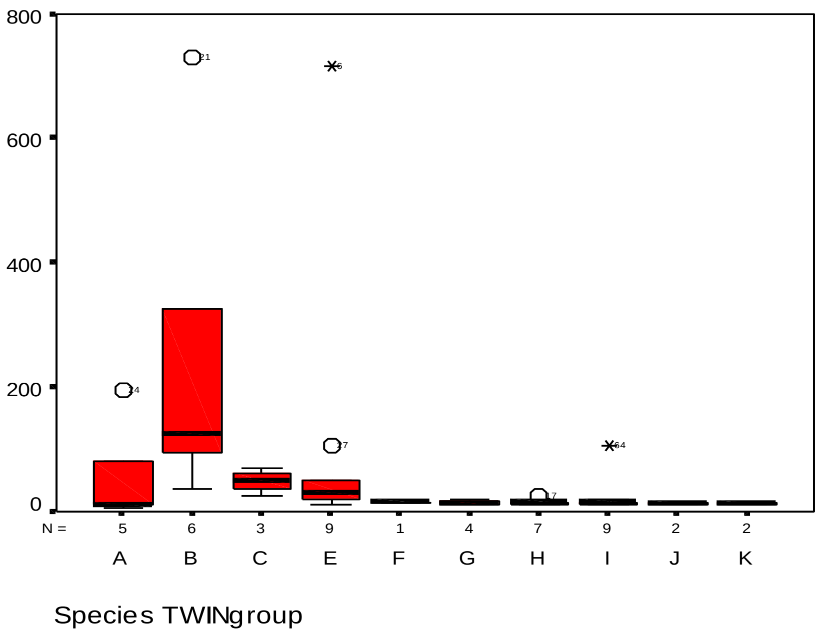


Figure 3.22 Species TWINgroup plotted against sodium cation levels

It can be seen that all of TWINgroup C training areas fall on slopes between 0 and 5° and all of TWINgroup E training areas fall between 0 and 10°. TWINgroup K has two of three training areas on very steep slopes. There is a definite steepening of slopes across the TWINgroups from A to K indicating that these species groupings are sensitive to slope.

There is a relationship between soil sodium cation levels and TWINSPAN species group. Figure 3.22 illustrates that TWINgroups B, C and E have higher sodium cation medians than groups A and F to K (group D is omitted as this group only has one training area and no soil sample was collected for its single training area). This soil chemistry difference is related to the geology. TRU sites have higher sodium values than MRU sites (only one soil sample was taken from a training area on Sorbas geology). Sodium levels appear to be related to the distribution of species in the field area and indeed the distribution of a salt tolerant plant, *Limonium insigne*, seems to bear this out as it is only found in training areas on TRU geology.

An investigation of TWINSPAN cover groups and the Normalised Difference Vegetation Index classification is discussed in section 6.4.

3.6.4.1 Summary of species TWINSPAN findings

The species data results are clearly cut by geology so that all the sites with any Sorbas member sediment and all but one on MRU sediment fall on the negative side of the initial split indicating a clear relationship between species composition and geology. Those training areas on the negative side of the split which are located in the Infierno catchment generally have a stony substrate and occur on ridges which are not, from observation, deeply incised. In the Mocatán catchment, these negative side sites are on ridge-tops containing a dense relict covering of shrubs All but one of the training areas on the positive side of the first cut level occur on the TRU and are mainly found on eroding pediments and abandoned agricultural terraces. These generally have a greater percentage of annuals and soft grasses such as *Hordeum spp.* and these are the only training areas where the salt tolerant plant, *Limonium insigne*, is found. These training areas also contain higher levels of soil sodium. Training areas are also separated by catchment, and to a lesser extent by slope.

3.7 Summary

DECORANA and TWINSPAN were chosen as the most appropriate analysis techniques to investigate the cover data and the species data collected in the field in 1997 and 1998. The aims of the analyses were to identify relationships between environmental variables and the distribution of the cover and species types across the study area. Interpretation of the DECORANA results, together with other environmental variables not included in the analyses, suggests that soil chemistry is one of the most important environmental variables affecting the distribution of cover types and catchment, as an analogue for geomorphological differences, is related to the distribution of species types. Other environmental variables showing relationships to cover and species distribution are, in descending order of importance, geology, slope and aspect. The distribution of training areas into groups by TWINSPAN indicates an association with geology for both species and cover data; there are associations with catchment, soil chemistry and slope for species, and catchment soil chemistry and aspect for cover data. Analysis of cover and species data collected in the field has enabled investigation of these data at a finer scale than could have been carried out simply by examining remotely sensed data. These analyses add value to the remotely sensed data, and will be used in the final analysis of the patterns of cover in the study area.

4 PHOTOGRAMMETRY: ITS APPLICATION TO AERIAL PHOTOGRAPHS OF THE STUDY AREA

4.1 Introduction

Photogrammetry is the “art, science and technology of obtaining reliable information about physical objects and the environment through the process of recording measuring and interpreting photographic images and patterns of electromagnetic radiant imagery and other phenomena” (American Society of Photogrammetry, 1980 p 1249). Vertical aerial photography can be used to determine various measurements and to create maps, including the height of objects in the photographs, distances between objects/landforms and Digital Elevation Models (DEM). Originally, aerial photographs were used to create hardcopy topographic maps, but with the advent of fast and easy to use remote sensing and photogrammetric software, accurate raster maps and DEMs can be created from scanned aerial photographs. This chapter introduces the theory behind rectification of aerial photographs and DEM production and production of DEM derivatives such as slope and aspect images. The rectification of aerial photography of the study area is presented, along with a DEM created from that photography and various products created from the DEM.

4.2 Photogrammetry

4.2.1 The geometric elements of an aerial photograph

Raw aerial photography imagery has large distortions caused by various factors and if an image is needed that is to conform to a map co-ordinate system, photogrammetric modelling has to be carried out. This removes the distortions in the photographs and produces a rectified image. Photogrammetric modelling is carried out using collinearity equations which eliminate the errors of distortion. Collinearity is the condition wherein the exposure station of any photograph, any object point on the ground co-ordinate system and its photographic image lie on a straight line. This condition holds no matter what the angular tilt on the photograph is. The collinearity equation is discussed and examples given in Lillesand and Kiefer (2000) and ERDAS (1999). A discussion of the geometry of aerial photographs can be found below, leading on to an explanation of the rectification process.

Photogrammetry involves establishing a relationship between the camera, the imagery and the ground. Each of these three variables has to be defined with respect to a co-ordinate space and system (ERDAS 1999). The camera geometry as it existed at the time of data collection is defined by interior orientation. The four components of camera geometry are as follows:

i) Principal point
ii) Focal length
iii) Fiducial marks
iv) Lens distortion

The principal point is mathematically defined as the intersection of the perpendicular line through the perspective centre of the image plane. Optically, this is difficult to determine, so the optical definition of the principal point is the image position where the optical axis intersects the image plane, and this is calibrated in a laboratory before flights as the principal point of autocollimation and the principal point of symmetry, both of which are contained in the camera calibration certificate which is prepared from these and other laboratory reports on the camera and lens (ERDAS 1999).

The focal length is the length from the principal point to the perspective centre. This again is defined on the camera calibration certificate from laboratory tests on the camera. Fiducial marks, which come in sets of four or eight, are found at the corners and/or the edges of the image and are used in the determination of the principal point for each image. The image positions of the fiducial marks are measured on the image and compared to the calibrated co-ordinates of each fiducial mark.

Lens distortion comes in two forms, radial and tangential. Distortion occurs when light passes through the lens and is bent, thereby changing direction and intersecting the image plane at positions that deviate from the norm. Radial distortion causes points on the photograph to be distorted along lines radiating from the principal point. This is often referred to as symmetrical lens distortion. Tangential distortion occurs at right angles to the radial lines from the principal point and the effect on the image is very small and is usually considered negligible. Lens distortion is usually determined in the laboratory before flights during the camera calibration process and is then recorded on the camera calibration certificate. (ERDAS 1999)

Exterior orientation defines the position and angular orientation associated with an image; it is associating the photograph with the ground surface photographed. The angular elements of exterior orientation describe the relationship between the ground and the image co-ordinate systems. The mathematics behind this orientation are described in ERDAS (1999).

In practise, modern software, such as ERDAS Imagine has automated many of the processes of photogrammetry. For any digital processing of the image to take place (e.g. rectification) a relationship between the camera, the image and the ground must be defined. The variables of exterior orientation, interior orientation and accurate ground representation need to be defined. Interior orientation parameters are usually known from the camera certificate included with the aerial photography, but exterior orientation parameters are not normally known. Exterior orientation is the position of the aircraft and therefore the camera lens in the air related to the ground. The position of the aircraft can be derived from the collinearity equation when the appropriate inputs are made into the ERDAS Imagine rectification software.

The ERDAS Imagine software allows interior orientation figures to be input for a particular photograph. Ground control points (GCPs) are then collected. A GCP is a point with a known grid reference and height (X, Y and Z) that can be placed accurately on the aerial photography image. Accurate ground control is essential to almost all photogrammetric operations because photogrammetric measurements are only as good as the ground control on which they are based (Lillesand and Kiefer, 2000). Features such as road intersections, river junctions and field boundaries are often used as ground control points where these can be identified on the photography and on a map. GPS (Global Positioning System) equipment is also very useful for acquiring GCPs. The minimum number of GCPs needed for rectification purposes is three, but the more GCPs of known co-ordinates that are placed on an image, the more accurately the corrected aerial photograph will conform to a real world grid system. Depending on the input data, various photogrammetric techniques can be used to define the variables needed to solve the collinearity equation and so derive the exterior orientation (aircraft and camera position in space in relation to the image). These basic photogrammetric techniques, such as space resection and bundle block adjustment are explained in ERDAS (1999). With the ERDAS Imagine remote sensing software which was used during the course of this thesis it is possible to take the photogrammetry one step further and to orthorectify the imagery. The process of orthorectification which was carried out on the aerial photographs from the NERC 1996 flight over the study area is explained below.

4.2.2 Orthorectification

Orthorectification is "the process of removing geometric errors inherent within photography and imagery" ERDAS (1999 p303) These errors often include camera error as discussed above, topographic relief displacement and the curvature of the earth. Orthorectification takes raw digital imagery and applies a DEM and triangulation results to create an orthorectified image which is correct in X,Y and Z dimensions. The output image is one where every point looks as if an observer was looking straight down onto the ground from an orthogonal line of sight. Orthomax, (Vision International software run within ERDAS Imagine) is able to create DEMs and therefore orthophotos from scanned aerial photographs. Orthomax works by registering the scanned aerial photos to the original film co-ordinate system (interior orientation), carrying out photogrammetric block adjustments using the least squares block bundle adjustment algorithm and then automatically collecting a user defined ground space matrix of elevations from triangulated imagery which is output as a DEM. The DEM is then used in Orthomax to create an orthorectified image which is an image where the effects of perspective and relief have been removed. The above Orthomax processes are explained in detail in ERDAS (1995).

4.3 DEM creation and orthorectification of the aerial photographs

Orthomax was used to carry out DEM creation and from this, orthorectification using aerial photos of the Sorbas basin acquired by NERC in 1996. The DEM was produced using the proprietary Vision International automatic DEM collection algorithm. This is classified as an area correlator in which patches of pixels are compared during a matching process. The primary correlation measure is by normalised cross-correlation which takes into account overall differences in contrast and brightness between image patches, which means that it is possible to correlate patches of pixels which are in shade in one image and in sun in the other. If there is a problem following the automatic correlation, elevations of points which were not successfully collected will be interpolated using groups of successfully correlated pixels surrounding the un-interpolated point (ERDAS, 1995). Three overlapping aerial photographs of the study area were scanned at 400 dots per inch (dpi) and imported into the Orthomax program. Fiducial marks were registered on all three photographs using figures from the camera certificate provided with the aerial photographs and interior orientation was carried out using the focal length and radial distortion figures from the camera certificate. After interior orientation was completed, GCPs in three dimensions (x, y and z) were collected from various points that could be identified from a 1:10 000 map of the field area. These GCPs included river junctions, road junctions and other man-made features. Approximately 15 GCPs were collected for each photograph. Features that could be seen in the overlap areas of the photographs were needed as control points, because only by registering the same point on two photographs could the DEM creation take place (see Figure 4.1). After collection of GCPs a triangulation was run by Orthomax and the GCPs were assessed for their accuracy. If a GCP placement was inaccurate, it could be moved or deleted to give a better result. Once this had been done, the DEM tool was run to create a digital elevation model of the area where the photographs overlapped (Figures 4.2 and 4.3). The DEM created had a pixel size of 2x2m. An orthoimage could then be created from the DEM and the aerial photographs that had been used to created the DEM. This process was carried out using the ortho tool in Orthomax and a rectified aerial photograph with a pixel size of 1.7x1.7m was produced (Fig 4.4).

The DEM in Figure 4.2 appears ragged around the edges. This is because the DEM did not resolve towards the edges of the aerial photographs, a frequent problem with DEM creation as the distortion of an aerial photograph increases towards the edges. Also, in this case it was difficult to find good placements for GCPs close to the edges of the photographs. Distorted areas were removed in order to produce a reliable DEM covering most, but not all, of the study area. Dark tones in Figure 4.2 represent low elevations with progressively lighter tones indicating higher elevations. Stream channels can be identified on the grey scale image, but the relief patterns stand out more clearly in the coloured version in Figure 4.3. The orthoimage in Figure 4.4 was created from two orthorectified images (i.e. from two DEMs and associated three aerial photographs) and hence shows a larger area.

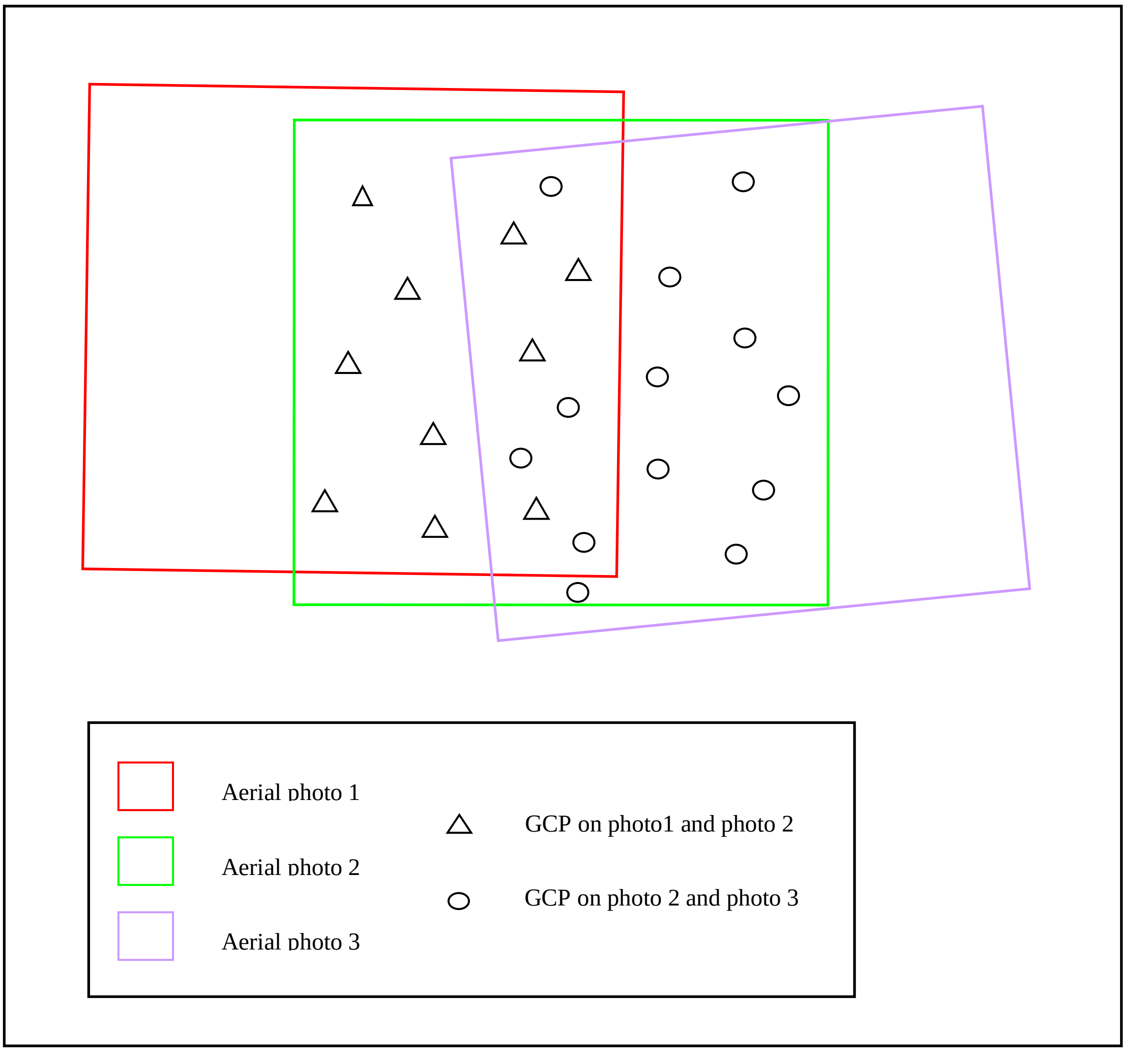


Figure 4.1 Positioning of GCPs on aerial photographs in Orthomax

These two orthorectified images were mosaiced together in ERDAS Imagine. Mosaicing is a process that allows two images to be 'stitched' together and become one. However mosaicing is not recommended for 'stitching' DEMs together as it has a tendency to alter pixel values along the join (ERDAS, pers comm 2001). Whilst this pixel value change is acceptable for an image (as in Figure 4.4) which purely displays the reflectance of the ground cover, it would alter the height values in the pixels of the DEM and thus impose inaccuracies upon any downstream analysis. The irregularity of the image is caused by flaws at the edges of both the DEM and the orthorectified photograph which resulted from failure of the Orthomax software to resolve properly in these areas. This failure resulted in anomalous areas in the image which had a 'smeared' or distorted appearance. Such areas have been removed to improve clarity.

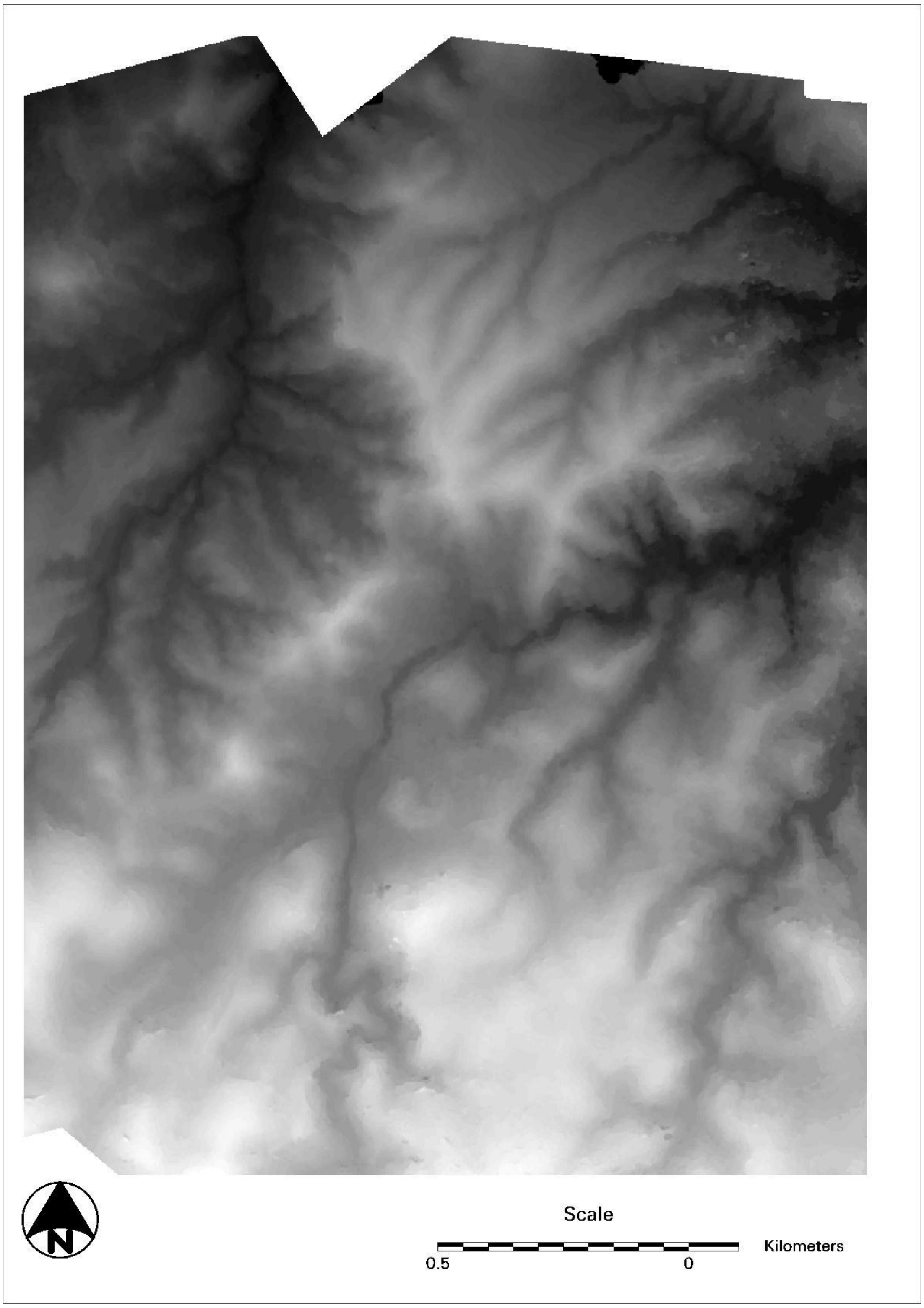


Figure 4.2 DEM of the study area created in Orthomax

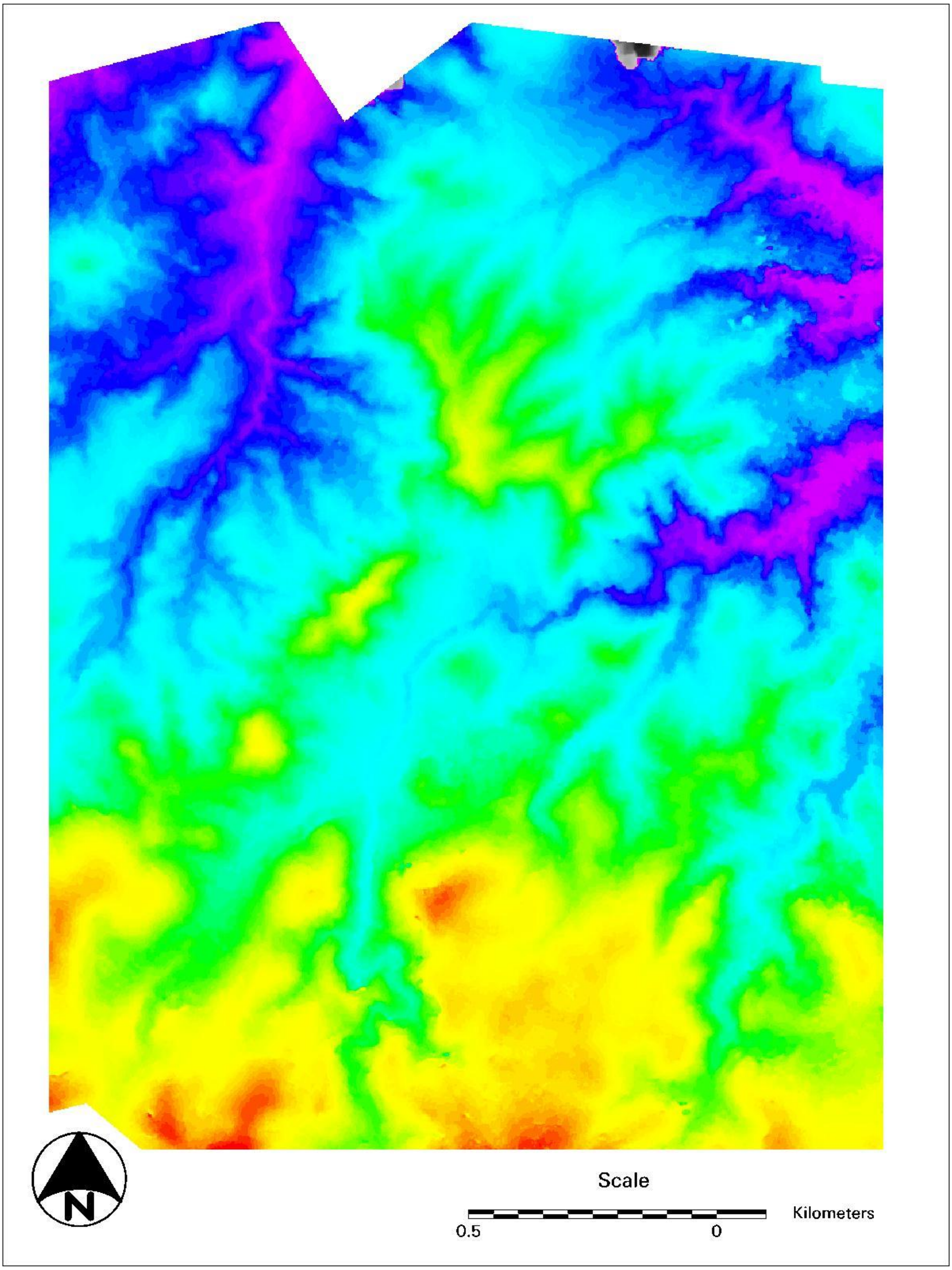


Figure 4.3 Colourised version of DEM of the study area. Red is highest relief, purple is lowest.

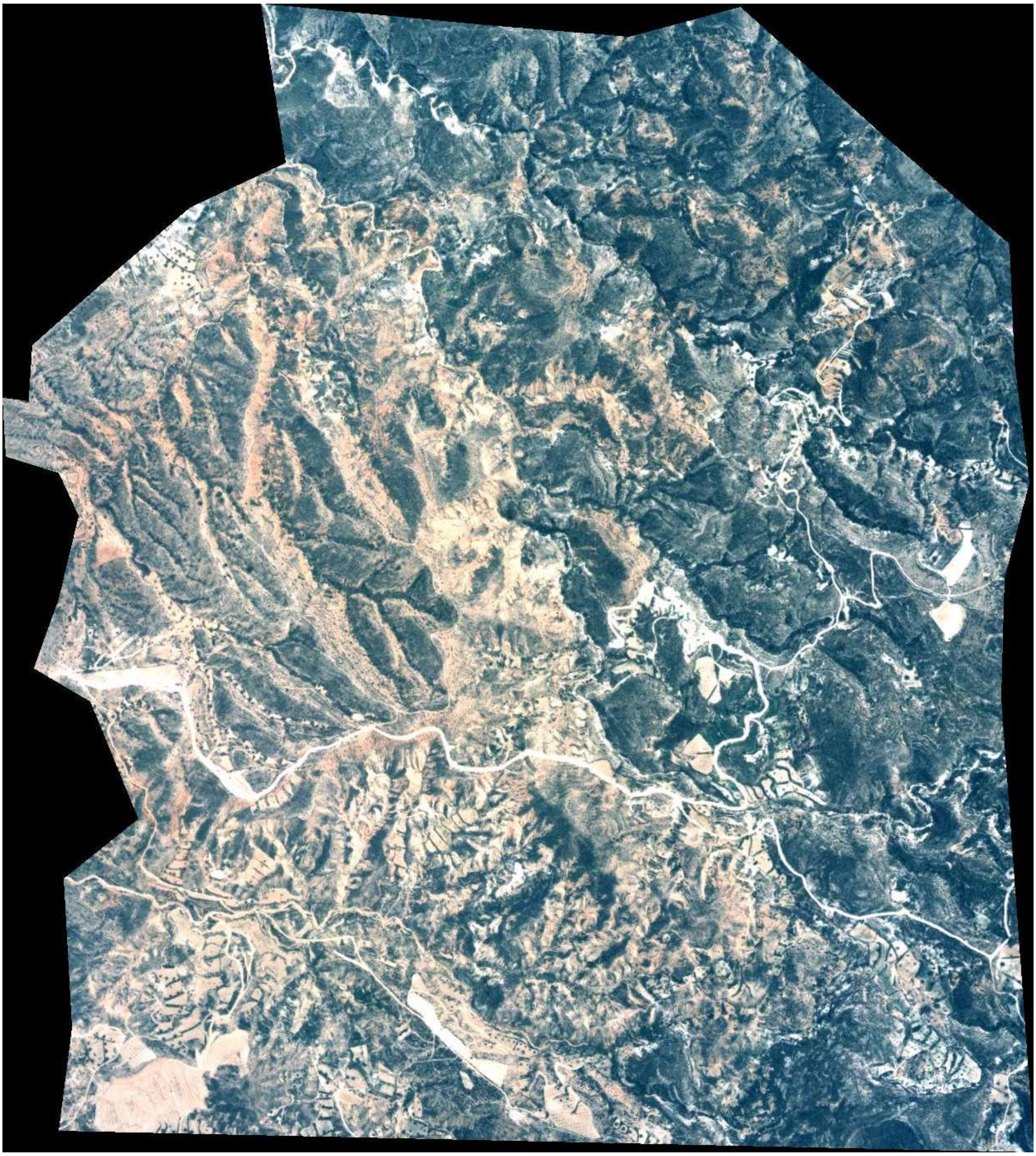


Figure 4.4 Orthorectified aerial photograph of the study area created in Orthomax

4.3.1 Uses of the DEM

A raster DEM was produced and used in this study, primarily because that was the only form of elevation data that could be created from the aerial photographs with the resources available and secondly because the nature of the software used (raster based) dictated that a grid DEM would be the most useful format in which to hold elevation data for further analysis. As well as producing an accurate model of terrain, a DEM can be used to derive land surface parameters such as slope, aspect, slope concavity/convexity, contributing area and drainage density (Garg and Harrison, 1990; Burrough and McDonnell, 1998) and also to map flow networks and analyse hydrological problems (Burrough and McDonnell, 1998; Tarboton, 2000; Tarboton and Ames, 2001).

4.3.1.1 Slope derivation

Slope is expressed as the change in elevation over a specific distance. The specified distance in a DEM is the pixel size. ERDAS Imagine (1999) uses a 3x3 pixel window to calculate the slope at each pixel, either in degrees or as a percentage. Figure 4.5 shows a pseudocolour slope image derived from the DEM of the study area using ERDAS Imagine.

4.3.1.2 Aspect derivation

In the derivation of aspect from a DEM, each pixel is coded according to the prevailing direction of the slope at each pixel, and this is expressed in degrees from 1 to 360. The means of deriving these data from a DEM is similar to that used for slope derivation. A 3x3 pixel window is used to calculate the prevailing direction that the central pixel faces (ERDAS Imagine, 1999). Figure 4.6 shows an image of aspect in the field area. This image is displayed as greyscale with a different shade for each of the 360 degrees of aspect. Figure 4.7 shows the study area aspect figures divided into eight different classes in order to aid interpretation, although obviously at the expense of detail. In order to avoid problems caused by irregular borders, the images in Figures 4.5, 4.6 and 4.7 were taken as subsets of the original DEM.

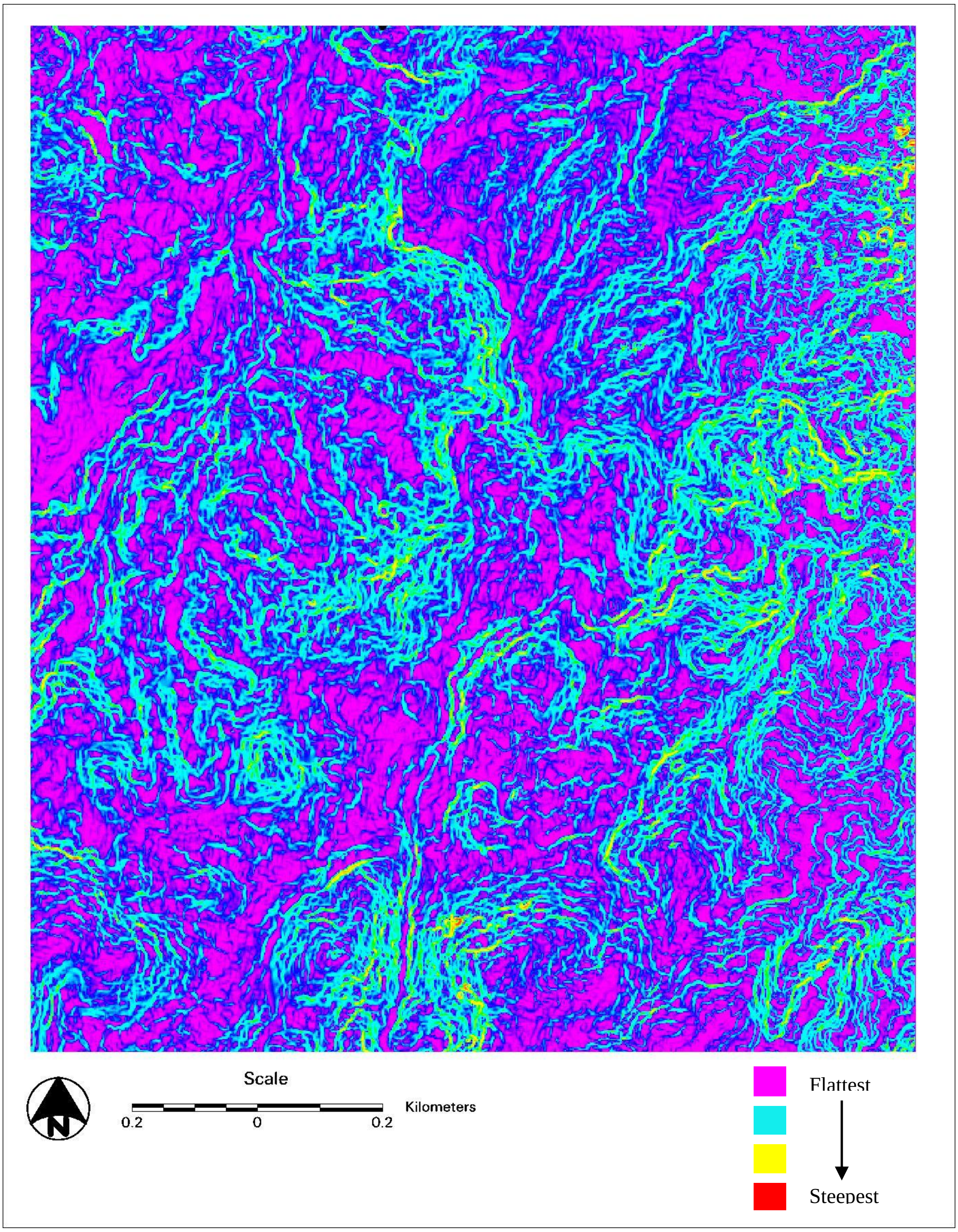


Figure 4.5 Slope image of the study area produced from the DEM

Figure 4.6 Study area greyscale aspect image

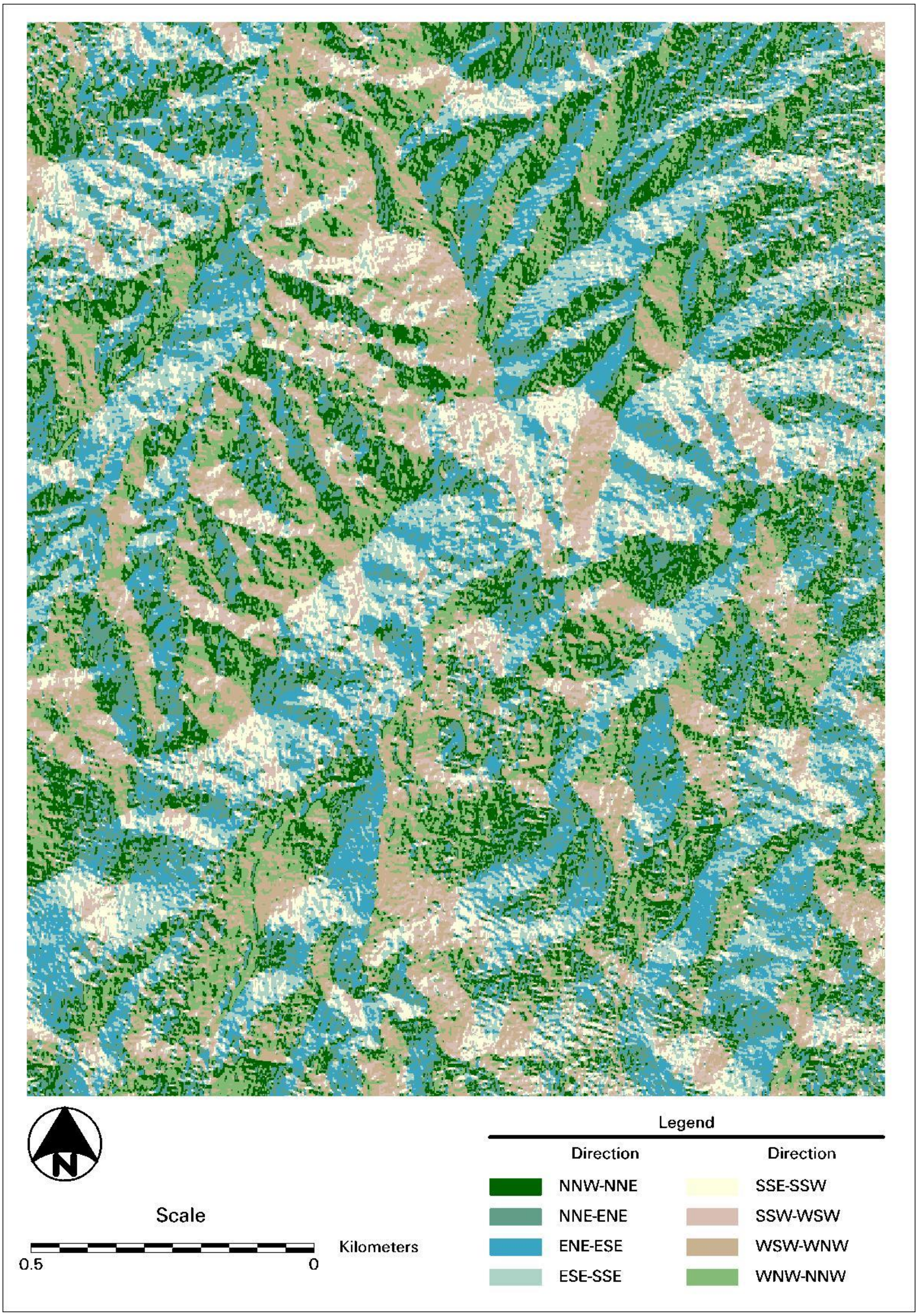


Figure 4.7 Image showing aspect divided into eight classes

4.3.1.3 Image draping

One of the most effective tools for visualisation is that of the image drape. This is where a rectified aerial photograph or other image is ‘draped’ over a 3D display of a DEM. The ERDAS Imagine software, Virtual GIS (VGIS) is a 3-D visualisation tool allowing 2-D images to be placed over a 3-D ‘frame’ of a DEM thus allowing the original 2-D image to be viewed in three dimensions. The software allows the user to create ‘fly-throughs’ of images used. A flight path can be digitised and the image on the DEM frame will be rendered as if the user is flying across the terrain. VGIS was used to produce the draped images shown on the following pages in plates 4.1, 4.2 and 4.3. These images demonstrate the power of this tool even when placed on a flat page rather than viewed on screen. They are screen dumps taken from a VGIS project which uses the study area DEM overlaid with the rectified aerial photographs and show oblique views of the study area.

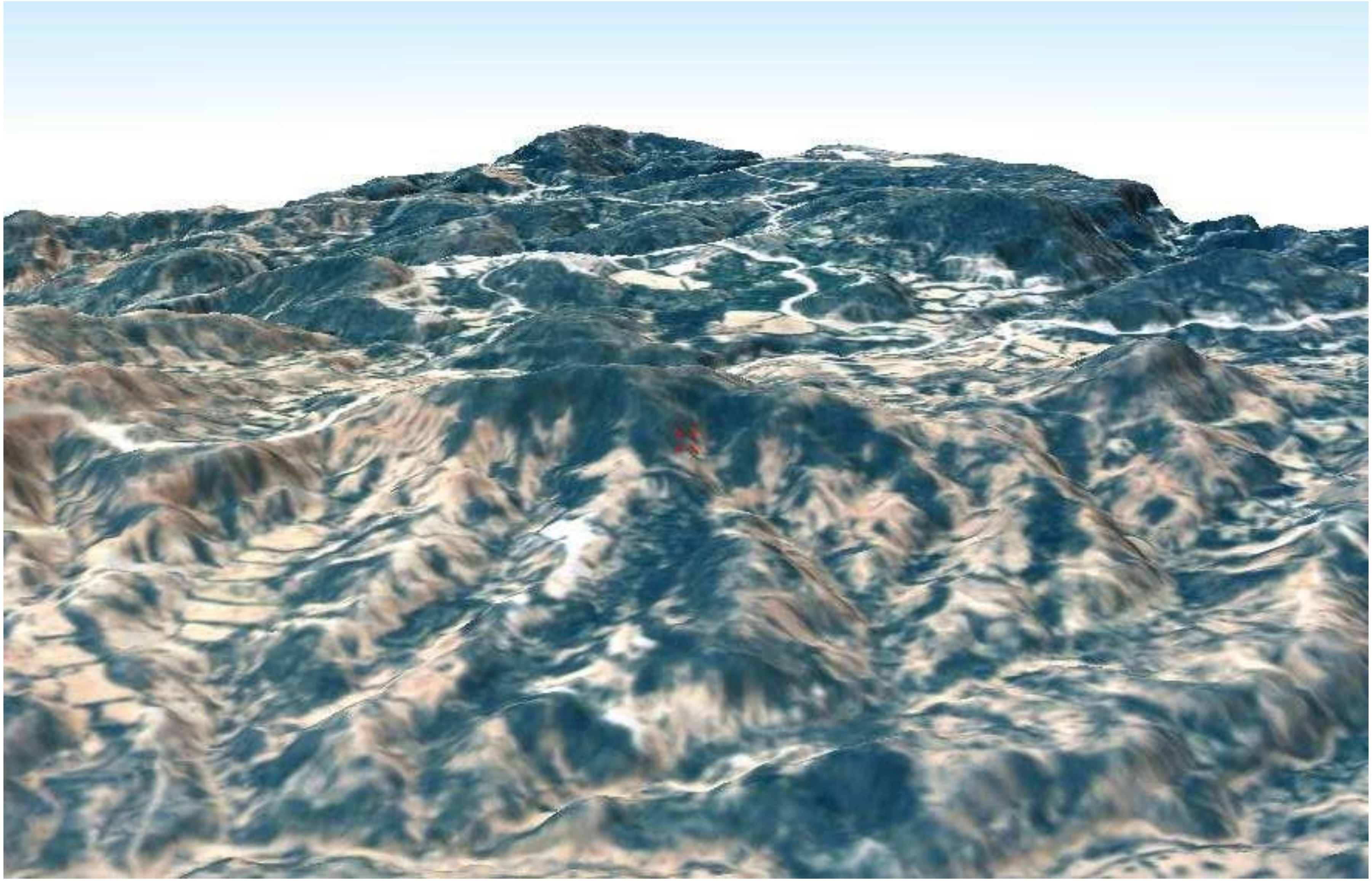


Plate 4.1 Looking south . Cerro de Juan Contreras in the foreground, Sorbas member hills in the background

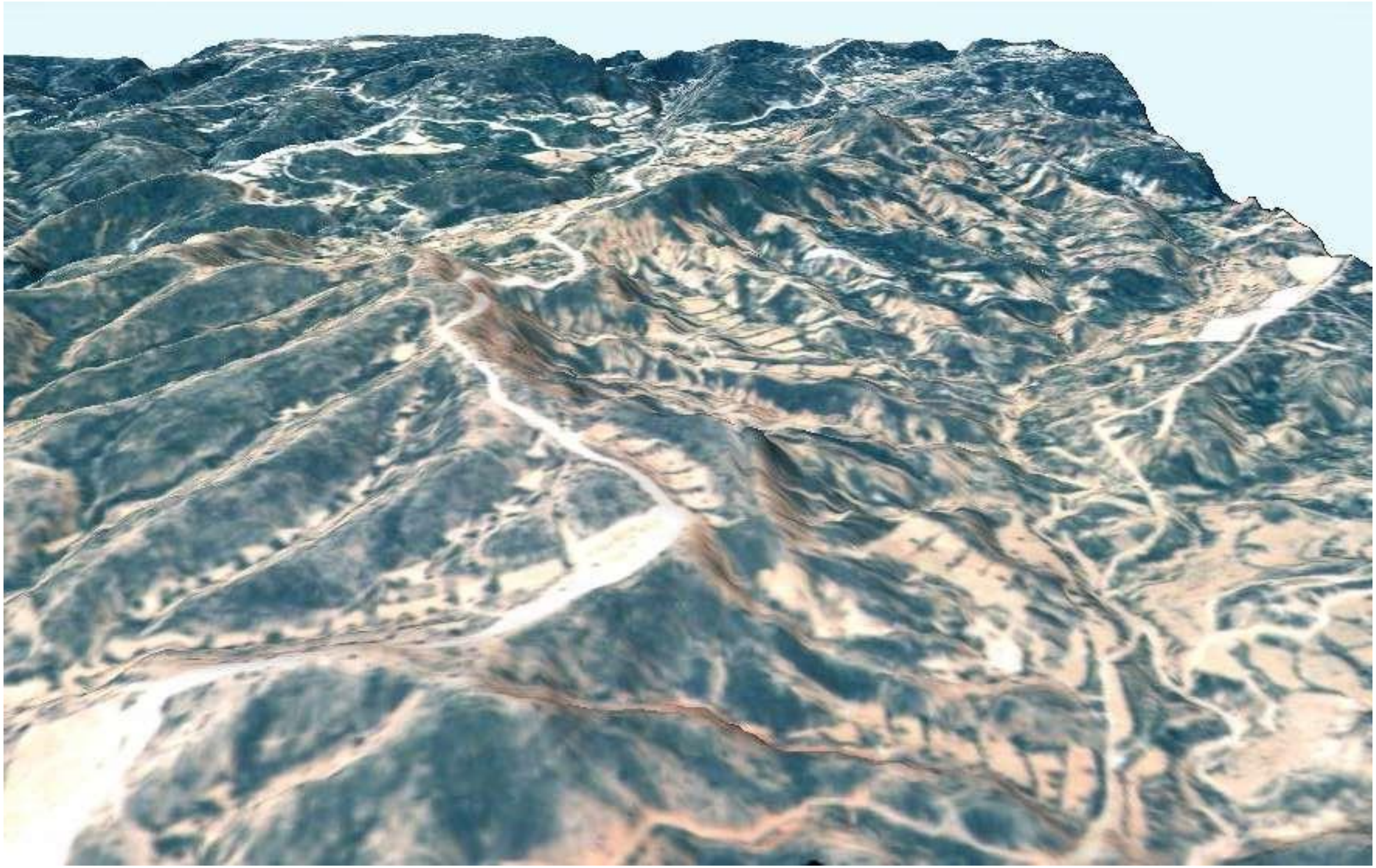


Plate 4.2 Looking south-west along the Rambla Mocatán valley

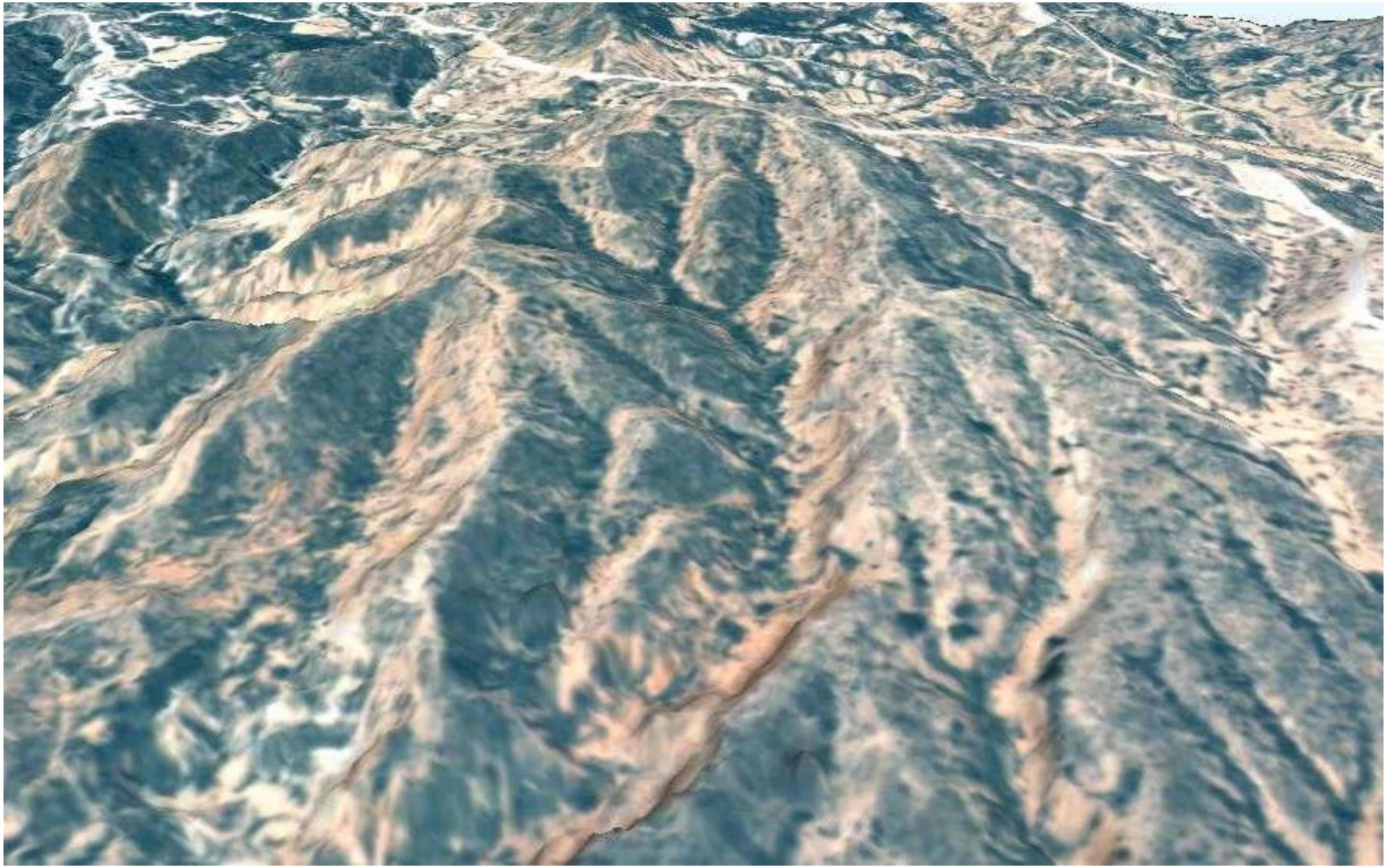


Plate 4.3 Looking WSW up to the headwaters of the Barranco Infierno

4.4 Quantitative landscape analysis using DEMs

Digital Elevation Models can be used to delineate flow paths and therefore drainage networks. According to Tarboton and Ames (2001), although field mapping is the most accurate way of identifying and mapping channel networks, DEM derived flow networks are an adequate substitute and are by far the quicker, more practical option when looking at a catchment on the meso-scale or above. Burrough and McDonnell (1998) comment that qualitative analysis of aerial photos through a stereoscope for drainage network derivation was tedious which often led to errors being made, and the automatic derivation of these attributes through quantitative analysis of DEMs is far more accurate.

To derive a drainage network from a DEM, a determination of routing is needed The flow of material over an elevation surface (i.e. a DEM) is determined by considering the direction of steepest downhill descent. (Borough and McDonnell, 1998). According to Tarboton (2000) the simplest method for specifying flow directions is to assign flow from each grid cell to the one of its surrounding neighbours which has the steepest slope. This is done in what is known as the 'D8' pattern as shown in Figure 4.8. The technique was introduced by O'Callaghan and Mark (1984) and is now widely used in drainage network derivation.

7	**6**	**5**
8	**0**	**4**
1	**2**	**3**

Figure 4.8 The D8 pattern for flow direction assignment

The target pixel is indicated by zero, and the eight surrounding pixels indicate the eight directions in which water could flow. The result of moving this 3x3 window over a DEM is to derive a new grid containing local drainage directions. Each cell in the new grid contains an integer between one and eight representing 'flow direction' unless there is sink or pit at the target pixel, in which case water cannot continue to flow on the surface and is given a number of 0, so the possible value that a cell in the new grid can be attributed with lies between 0 and 8 (Burrough and McDonnell, 1998).

In order to derive drainage networks a freeware DOS program called TARDEM was downloaded from the internet (www.engineering.usu.edu/dtarb). TARDEM is a program that has a number of steps which allow the creation of drainage and stream order images which can be used as input to the creation of a wetness index map (see section 4.1.1.7). TARDEM is configured to work best with ESRI ArcView but, there is a 'stand alone' version which is also available. Use of the stand alone TARDEM required an ASCII grid of the study area DEM. This was created by exporting the DEM from ERDAS Imagine to a .grd file format and changing the header information to fit the information needed by TARDEM to run the routine. TARDEM was run using the following commands (taken from Tarboton, 2000).

Flood: this took the .grd DEM file as input and produced a grid file with pits filled, using a flooding algorithm. Pits are generally erroneous local depressions in the DEM which result from errors in DEM production rather than genuine hydrological sinks[2]. These minima cause difficulty for water flow simulation algorithms and most software programs which simulate water flow require a preliminary pit filling step to eliminate these false depressions. Pit filling changes the relative elevation of the area of the DEM where water will not flow by filling the depressions until flow can take place across the surface (Caccetta, 1999).

D8: this routine took the pit filled elevation data and produced D8 flow directions, 'p', and slopes, 'sd8', for each grid cell. In flat areas flow directions are assigned away from higher ground and towards lower ground using the method of Garbrecht and Martz (1997).

Aread8: the D8 output, 'p', was taken as input to this routine which produced a contributing area value for cells, where the cell value is the number of grid cells draining through that particular cell. This was the particular image that was needed as input for the derivation of a wetness index.

Gridnet: this routine took as input the D8 output file 'p', and produced three more grid files.
'plen' in which each cell contains the path length from the furthest cell that drains to that cell.
'tlen' in which each cell contains the total length of all paths draining into it.
'gord' in which cell contains the Strahler stream order associated with it for a flow network derived using the D8 flow direction and upstream data. Strahler order is defined as follows. Pixels with no other pixels draining into them are order one. When two (or more) flow paths of different order join, the order of the downstream flow path is the order of the highest incoming path. When two flow paths of equal order join, the downstream flow path is increased by one (e.g. two order three streams joining make the channel downstream order four). The Strahler stream order image created from the TARDEM program can be seen in Figure 4.9 and an image of the Strahler stream order overlaid onto the study area DEM can be seen in Figure 4.10. These images aid visualisation of the two catchments where it can be seen that the Barranco del Infierno has a higher stream order than the Barranco del Mocatán. However, as neither of the catchments are contained entirely within the study area DEM the

[2] This statement may be open to question in the study area terrain, as water running in some parts of the catchments in question would 'disappear' into pipes or gullies too small to be registered by the 2m resolution of the DEM. However, pit filling was carried out as it enables TARDEM to operate correctly.

main channels are both likely to have higher stream orders than those shown. The DEM cuts off both of the main channels well below their sources.

All of the TARDEM routines produced image files in ASCII format. In order to view these files, they were imported back into ERDAS Imagine as georeferenced .img files. They could then be used alone (in the case of the Strahler stream order file) or as input into a model to create a wetness index image.

4.4.1 The Topographic Wetness Index

A wetness index is one of the more commonly used indices (Caccetta 1999) derived from DEMs and its equation is shown below

$$\text{wetness index} = \ln(A_s / \tan\beta)$$

Where A_s is the contributing catchment area in m² (number of upstream elements x the area of each grid cell) and β is the slope measured in degrees (Beven and Kirkby, 1979). A model was created in ERDAS Imagine's Model Maker facility where the Aread8 image from TARDEM and a slope image created in ERDAS Imagine were put into the equation above. The wetness index image produced is shown in Figure 4.11. Figure 4.12 shows the wetness index image draped over the study area DEM. This aids visualisation of the wetness index as it can be seen that there are higher index values in concave depressions and on the valley floors than on the ridges and convex areas of slope.

Regions of a landscape that drain large upstream areas or that are very flat give rise to high index values, and it is these areas that are most likely to become saturated after rainfall events (http://earth.agu.org/revgeophys/hornbe01/node9.html). The reason behind creating the wetness index image was to discover whether the areas that are topographically most likely to be wet during rainfall events have more vegetation than those with smaller contributing areas. The results of a comparison between the wetness index and vegetation cover are presented in Chapter 6.

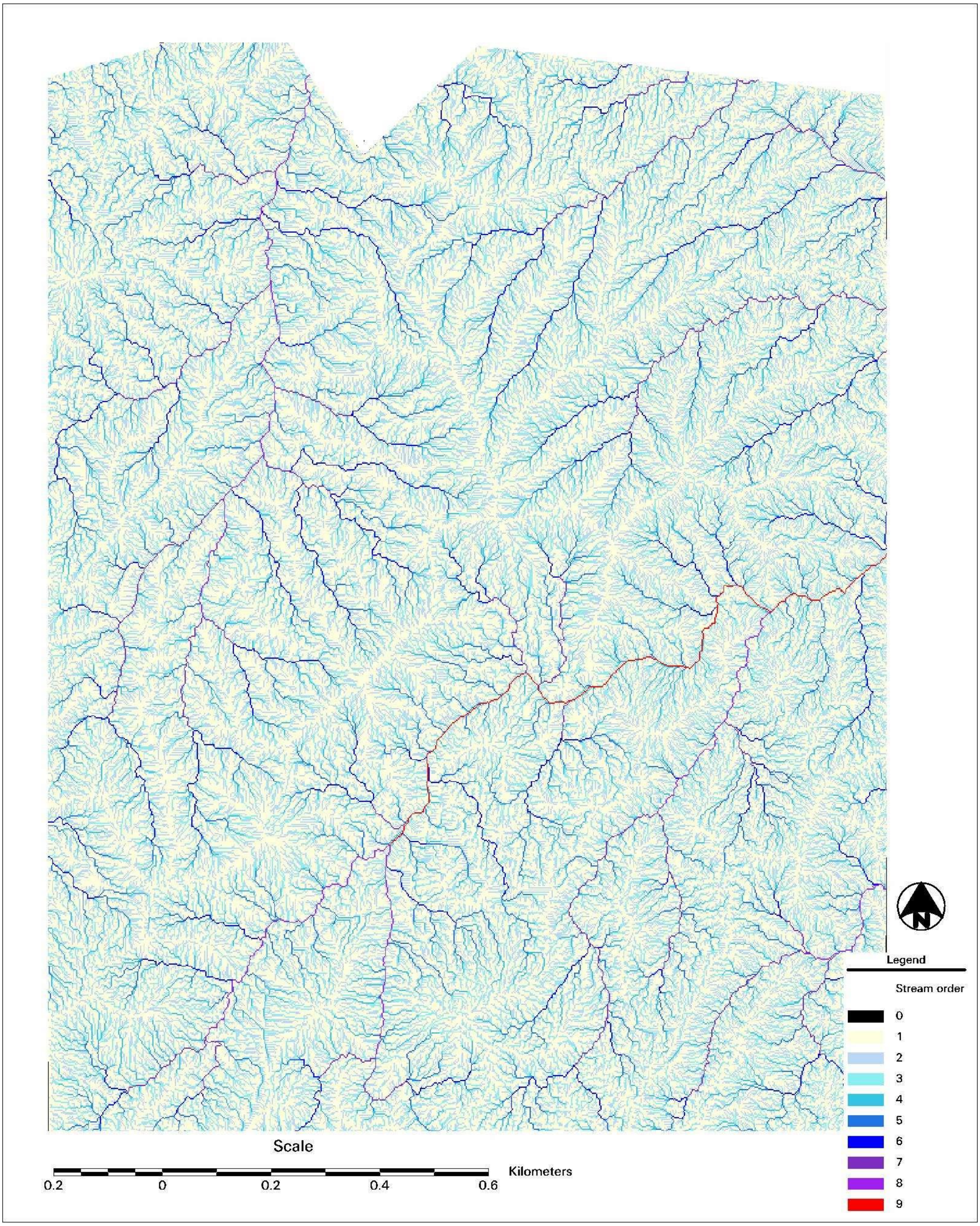


Figure 4.9 Strahler stream order within the Infierno and Mocatán catchments

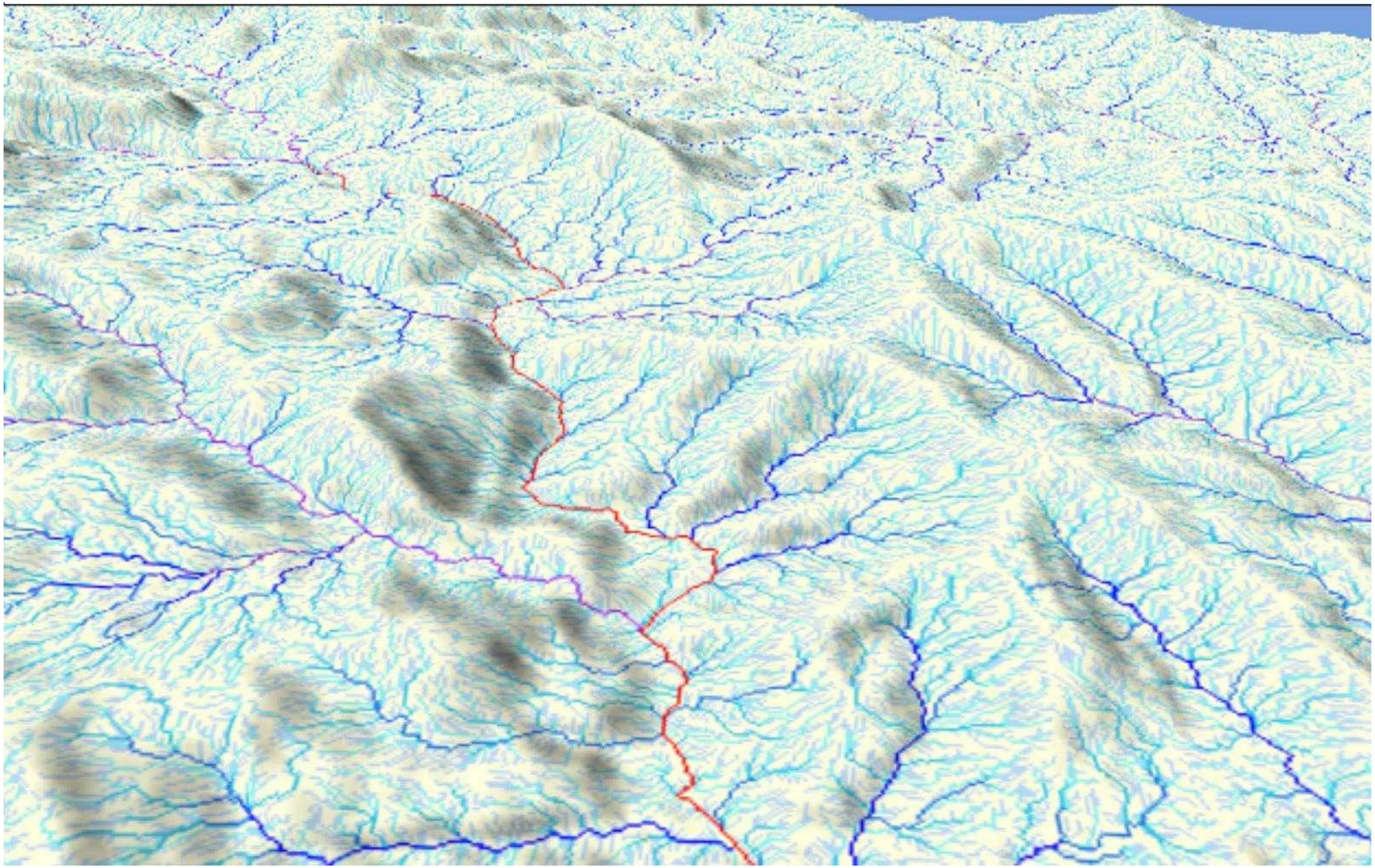


Figure 4.10 Strahler stream image showing the Infierno catchment draped over the catchment DEM

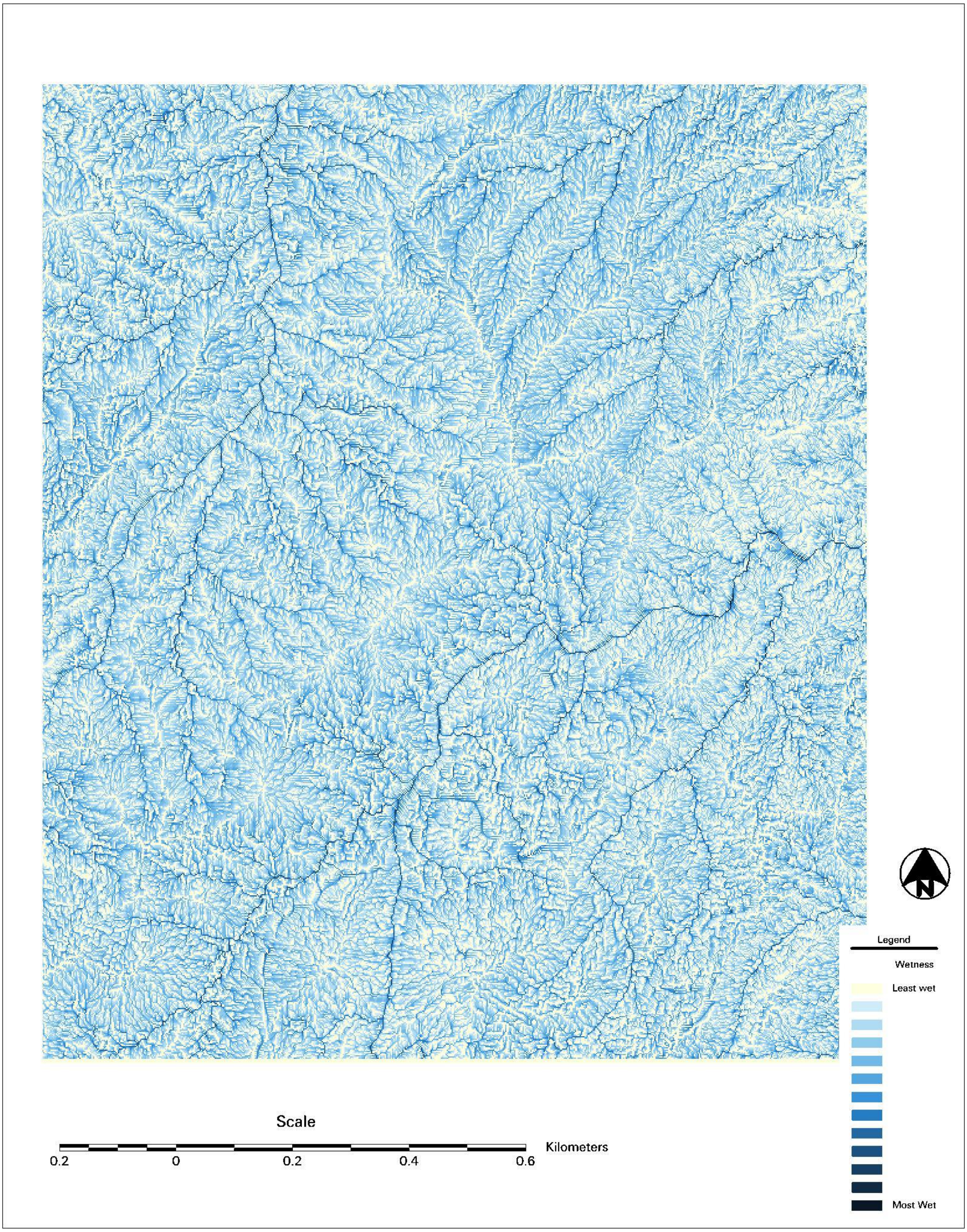


Figure 4.11 Wetness index image of the study area

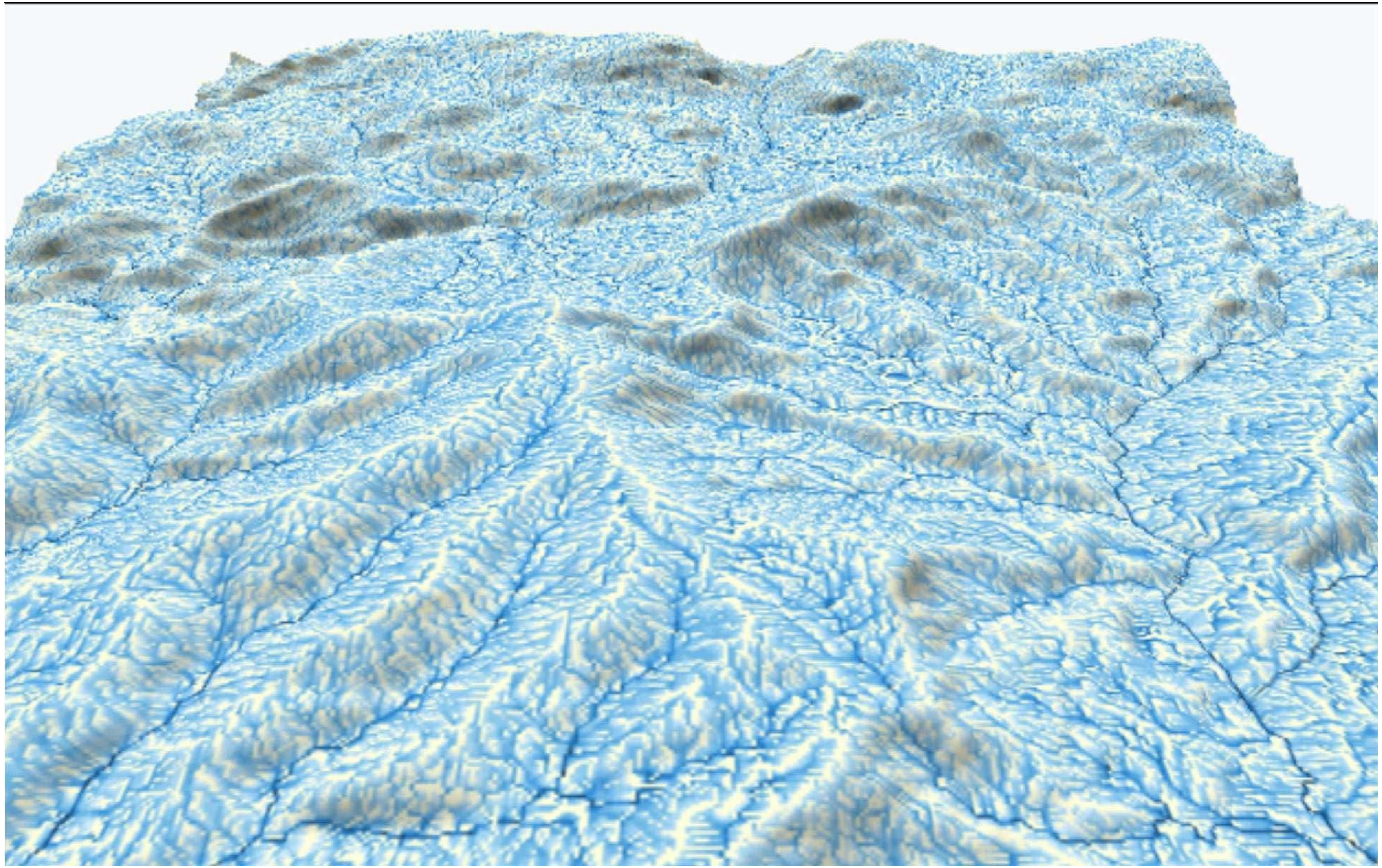


Figure 4.12 wetness index image of the watershed between the Mocatán and Infierno catchments draped over the DEM

4.5 Summary

The rectification of the aerial photographs of the study area allowed the derivation of a DEM of the study area. This enabled the creation of images of slope, aspect and wetness of the study area. These images have enabled visualisation of the study area, especially when used with the Virtual GIS software. The rectification of the aerial photographs was also beneficial to the process of investigating the landcover using the Airborne Thematic Mapper data as discussed below in Chapter 5, as the superior resolution enabled more detail to be observed when compared with the 5m resolution ATM data. The rectified aerial photographs were also useful as a map of the field area which allowed the accurate overlay of training area positions and investigation of what lay within those training areas. The next chapter presents the results of processing and analysis of the ATM data, which were collected by NERC at the same time as the aerial photography. The results of the use of the three DEM products in landscape analysis are presented in Chapter 6, where they are used to investigate the relationship between landcover and aspect, slope and wetness.

5 REMOTE SENSING FOR VEGETATION MAPPING AND ANALYSIS

5.1 Introduction

Chapter 5 sets out to describe techniques that can be used for vegetation mapping and analysis using multi-spectral images. Image enhancement techniques are examined with particular reference to vegetation indices. Examples of the use of vegetation indices in semi-arid areas for vegetation analysis are given, concentrating mostly on the Normalised Difference Vegetation Index (NDVI). Ground truthing for guiding interpretation of imagery is discussed. The acquisition of data in 1996 for this thesis by the Daedalus Airborne Thematic Mapper is then reviewed with a discussion of the particulars of each band that was acquired. Finally the methods used to analyse the data for investigation of the vegetation in the study area are presented.

5.2 Image enhancement

Enhancement generally involves techniques for increasing the distinction between features in an image to enable easier interpretation of features in the landscape that is imaged. New images are created from a raw (unprocessed) image to increase the amount of information that can be seen in the scene (Lillesand and Kiefer, 2000). Enhancement can be carried out on individual bands of an image (for example, histogram stretching, spatial filtering or convolution – see Lillesand and Kiefer (2000)), or using more than one band of data. This is known as vector image transformation and is discussed below.

5.2.1 The nature of vector image transformations.

A pixel in a single band (scalar) image is represented by one digital number (DN). A pixel which is represented by more than one band has several (a vector of) digital numbers. A pixel in a red-green-blue image on screen has 3 digital numbers for each pixel representing the three scalar images that make up the whole image, that of the red band, the green band and the blue band. Vector image transformations can be used to accentuate features in the landscape that the image shows. The same pixel in the different bands of an image can be added, subtracted, multiplied and divided to highlight spectral features in the landscape that would otherwise remain hidden. (Wilkie and Finn, 1996).

Subtraction of one image from another is useful for detecting temporal change in a terrain that has been imaged over a period of time. Multiplication of bands is often used to reduce the effect of haze in an image. Addition of images is not generally used as it does not have a useful function on its own. However, addition of masked images is often used as part of a more complicated process. Image division is the most useful arithmetic operation carried out on bands in a multi-spectral image (Wilkie and Finn, 1996). The images produced from division are known as ratio images.

5.2.1.1 Spectral Ratioing

Band ratios are quotients between measurements of reflectance in different spectral areas. Ratios are particularly effective at revealing latent information where there is an inverse relationship between different spectral responses to the same physical phenomenon (Campbell, 1996). Where there is a difference in spectral response, a ratio of the bands will provide a single value that expresses the contrast between the reflectances of the two bands (Campbell, 1996). Ratio images are most often created by combining visible red and near infra-red bands (NIR). This type of ratio with this combination of bands is found to create images that effectively discriminate between soil, water and vegetation. This combination can also help to remove shadows caused by topography (Wilkie and Finn, 1996). The most popular ratios for discriminating between vegetation and other landscape elements are the vegetation indices. A vegetation index is created by taking two or more bands which are added multiplied and/or divided to yield a single value which indicates the amount of vegetation (or the vigour of vegetation) in each pixel. The simplest vegetation indices are ratios between two digital numbers from different spectral bands.

5.2.1.2 Vegetation Indices

Living vegetation is particularly suitable for identification using ratioing as there is a strong inverse relationship between the spectral response of plants in the red and infra-red (IR) bands. Red light is strongly absorbed by vegetation and IR has a high degree of reflectance from vegetation. This means that the R/IR ratio will be high. Non vegetated areas will not display this response, and so a discrimination can be made between the response in the red band and the response in the near-IR band. Simple ratioing of spectral bands is not as effective at extracting information about vegetation as using a multiratio vegetation index because it offers insufficient standardisation (Curran, 1980)

Vegetation indices are quantitative measures of biomass and plant vigour (Campbell, 1996). Indices have been shown to be well correlated with vegetation cover, leaf area index, biomass and absorbed radiation in the chlorophyll absorption section of the spectrum (Wyatt, 2000). One of the most often used vegetation indices is the Normalised Difference Vegetation Index (NDVI) which is calculated as:

$$NDVI = \frac{IR - R}{IR + R}$$

This index corresponds to the following bands from Landsat TM and the Daedalus ATM sensor:

$$NDVI = \frac{\text{Landsat band 4 - band 3}}{\text{Landsat band 4 + band 3}} \qquad NDVI = \frac{\text{ATM band 7 - band 5}}{\text{ATM band 7 + band 5}}$$

This vegetation index offers simplicity, a high degree of standardisation and there is no assumption about the distribution of the data (Curran, 1980). It offers the same kind of information as a simple ratio (e.g. R/IR), but is defined to produce desirable statistical properties in the results that it produces (Campbell, 1996). The multispectral reflectance ratio is actually a measure of vegetation amount and productivity. Curran (1980) gives the example of a stand of low vegetation amount undergoing a period of active growth which would readily absorb red light to use for photosynthesis. This would cause the stand to have a greater IR to R difference than a stand of more dense vegetation with slower growth, and it would therefore have a higher NDVI value than the latter stand. There are many other vegetation indices that it can be possible to derive from multispectral data, some of which are summarised in Table 5.1.

Table 5.1 Some vegetation indices and their uses (adapted from Ray, 1994).

Index	Calculation	First described	Explanation of use
Ratio Vegetation Index	$RVI = \frac{\text{NIR}}{\text{Red}}$	Jordan 1969	The most widely used vegetation index. However it is not normally used now for calculating vegetation amounts as an end gaol, but used in processes to remove albedo effects.
Normalised Difference Vegetation Index	$NDVI = \frac{\text{NIR - Red}}{\text{NIR + Red}}$	Concept first presented by Kriegler *et al* (1969) and ascribed to Rouse *et al* (1973)	This index gives a similar result to the RVI but has the advantage in varying from 1 to –1 whilst the RVI ranges from 0 to infinity. It is a ratio based index with isovegetation lines† converging at the origin.
Difference Vegetation Index	DVI = NIR-Red	Richardson and Everitt (1992) but in common use before this as VI (vegetation index) in Lillesand and Kiefer (1987)	This index is a perpendicular index that has isovegetation lines parallel to the soil line which itself has an arbitrary slope and passes through the origin.
Perpendicular Vegetation Index	*PVI* = sin(a)NIR – cos(a)Red where a is the angle between the soil line and NIR axis	Richardson and Wiegand (1977)	This is a generalisation of the DVI which allows for soil lines of different slopes. This index is sensitive to atmospheric variation
Weighted Difference Vegetation Index	WDVI = NIR-g*Red where g is the slope of the soil line	Clevers (1988)	WDVI is similar to PVI but has an unrestricted range of values. It too is very sensitive to atmospheric variations.
Indices to minimise soil noise ††			
Soil Adjusted Vegetation Index	$SAVI = \frac{\text{NIR - Red}}{\text{NIR + Red + L}}(1+\text{L})$ where L is a correction factor ranging from 0 for high vegetation cover to 1 for very low vegetation cover	Huete (1988)	This index attempts to be a hybrid between ratio and perpendicular indices and it acknowledges that isovegetation lines are not parallel and do not all converge at a single point. This index was originally based on measurements of different canopies on light and dark soils. The adjustment value L was found by trial and error until a value was found that gave equal vegetation index results for both dark and light backgrounds. An L value of 0.5 is generally used in most applications for intermediate densities of vegetation. The nature of the calculation of SAVI means that it defaults to NDVI values when the value of L is 0 (i.e. high vegetation cover values).

Modified Soil Adjusted Vegetation Index	$MSAVI2 = (1/2)*(2(NIR+1) - \sqrt{((2*NIR+1)^2 - 8(NIR - RED))}$	
	Developed by Qi *et al* (1994)	MSAVI2 is the second modified soil adjusted index developed by Qi *et al*. MSAVI1 was developed to solve the problem of the correction factor of L which is the circular idea of needing to know the vegetation amount before calculating the vegetation index. MSAVI2 eliminates some of the precalculation that MSAVI1 required. The MSAVI is ratio based and the isovegetation lines cross the soil line at varying points.

†There are basic assumptions made by the use of vegetation indices including the idea that all bare soil reflectance in an image will form a line along the lower right hand side of a scatterplot when red and NIR pixel values for the image are plotted as a scatterplot with red as the x-axis. This line describes the variation in spectral reflectance of bare soil in the image (Ray, 1994). Most of the commonly used indices are only concerned with red and near-infrared space, so a red and near-infrared line for bare soil is assumed. There are two lines of thinking on the nature of the orientation of lines of equal vegetation quantity (isovegetation lines) in comparison with the soil line: the first being that all isovegetation lines converge at a single point. Indices using this assumption are ratio based, for example, NDVI and SAVI. The second is that all isovegetation lines remain parallel to the soil line. These indices are known as perpendicular indices and measure the distance from the soil line to the red-NIR point of the pixel. Examples of these indices are the PVI and WDVI (Ray, 1994)

†† Different soils have different reflectance spectra. This means that the vegetation indices which assume that there is one soil line may have difficulty in distinguishing the vegetation in images where there are soils with more than one reflectance spectra. This is an especially acute problem in areas where vegetation cover is low. Vegetation indices that attempt to take soil reflectance into account do so by shifting the place where isovegetation lines meet. Soil noise is reduced at the expense of the sensitivity of the indices to vegetation. As a rule these indices are slightly less sensitive to vegetation cover in an image than NDVI at low levels of vegetation cover (Ray, 1994)

Which vegetation index should be used? This depends on the type of environment that is being investigated and the variation in soil within that environment. It also depends on the atmospheric noise in the image. Ray (1994) suggests that the NDVI is the best vegetation index to use in most cases. It is the most well known index, is simple and is trusted by other researchers. It has the best dynamic range of the vegetation indices and the highest sensitivity to changes in vegetation cover. Ray (1994) does comment that NDVI becomes less effective at low vegetation cover amounts, and should be used with care in areas with less than 30% cover. The most suitable vegetation index for areas with less than 30% cover, but above 15% cover is the SAVI.

Duncan *et al* (1993) undertook a comparative study of spectral vegetation indices which were used to observe shrub cover in the Jornada Basin in New Mexico. They assessed the statistical relationships between vegetation indices and shrub cover. Vegetation indices were shown to be sensitive to shrub cover, and to some extent species, and highly significant correlations were obtained between vegetation indices and cover. Their work indicated the potential for using multi-spectral, multi-temporal analysis to differentiate between shrub type and between shrubs and grasses. The research showed that NDVI, PVI and SAVI could all be used to identify areas of different types of vegetation, with each index being correlated with biomass in the area studied.

Shoshany (2000) reviews studies on the uses of NDVI to investigate biomass in Mediterranean regions, and most of the studies cited conclude that NDVI is a useful index for the measurement of vegetation quantity in these regions at the large scale (over small areas). In particular, Svoray (1996) using Landsat TM data, successfully identified six phyto-phenology classes using unsupervised classification of NDVI images on the Judean Plateau.

5.3 Ground truthing for remotely sensed imagery

5.3.1 A definition of ground truthing

Ground truthing is the term generally used for data collected in the field to guide the interpretation of and to verify information extracted from remotely sensed imagery (Lillesand and Kiefer, 2000). Justice and Townshend (1981) object to the term ground 'truthing' as this implies that the ground data are free from error, preferring the terms ground data or ground information. However as ground truthing is the term used in most texts it will continue to be used here. Ground truthing data can be subject to various errors including location errors, observations not being synchronous with image collection and errors from inadequate sampling design. It is very important to minimise these errors as the reliability of the ground truth will affect the validity of extrapolations about ground conditions in areas not visited in the field, which is after all, what remote sensing is about (Justice and Townshend, 1981).

Ground truth data collected in the field can take many forms including soil samples, vegetation survey, land-use survey and survey of the relief of the land. Ground truth data are needed to train computer or human classifiers to extrapolate what they know about the sampled area to the whole of the remotely sensed area. This is done using correlations between ground data and image properties. Assessment of the viability of these extrapolations is then needed. This requires further ground truthing to be carried out to evaluate the validity of the extrapolations that have been made from the first set of ground truthing (Justice and Townshend, 1981).

5.3.1.1 Choosing sites for ground truthing remotely sensed data

Field data collection, or ground truthing, should aim to characterise the landscape within an area rather than at a specific point in the landscape. To this end, it is generally found useful to create an initial map of land cover types and uses when remotely sensed data is first received, and then sampling should take place within each of these areas (Wilkie and Finn, 1996). Sites chosen for ground truthing are often known as training areas (they are used to train the remotely sensed data as explained above). Training sites chosen for sampling should be internally homogenous so that all features in a site are representative of only one land cover category. There are criteria for considering a site to be uniform in an area of complex terrain which have been drawn up by Justice and Townshend (1981). These criteria are:

The training area should possess one surface cover for more than 85% of the site
The distribution of cover types must be spatially uniform throughout the site
The aspect must have no more than 22.5% variation either side of the dominant aspect
The slope angle should have no more than 25% variation for no more than 20% of the training area.

In some areas which are very heterogeneous it may not be possible to find training area which are homogeneous. In cases like this it is up to the surveyor to make decisions on the internal variability allowed within each training area. Training areas should be large enough to be located easily in the remotely sensed data. This generally means that training areas should be more than one pixel in size. Justice and Townshend (1981) recommend that the minimum size of a training area should be

$$A=P(1+2L)$$

where P = the pixel dimensions and
L = the accuracy of location in terms of the number of pixels

Wilkie and Finn (1996) comment that training areas should consist of 3 to 5 pure pixels which could translate into an overall area as large as 20-40 pixels. There should be enough training areas so that they can account for the spectral response range of each land-cover category (Wilkie and Finn, 1996). Their guide to the number of training areas that should be sited within each class (identified from the preliminary look at the imagery), is that $50x$ pure pixels should be available to estimate the spectral response from each land cover class where x is the number of spectral bands to be used to estimate class spectral signatures. In heterogeneous landscapes like the study area, this means collecting as many training areas as time and resources allow as some of them are likely to contain mixed pixels although the aim is to maximise pure pixels.

5.4 Collection of multispectral images

A multispectral scanner operates over many spectral bands rather than just the three bands it is normal to find in photographic images (red, blue and green or red, green and IR). This allows more information to be collected than with conventional photography or limited band sensors. This section will concentrate on one type of multispectral scanner, the Daedalus 1268 Airborne Thematic Mapper (ATM), which was used to collect data during the NERC flight over the Sorbas Basin in 1996.

5.4.1 Daedalus Airborne Thematic Mapper

The Daedalus 1268 scanner is known as an across track or whiskbroom scanner. It uses a rotating mirror to scan the terrain along scan lines that are perpendicular to the flight line. The scanner repeatedly measures the electromagnetic radiation (EMR) from one side of the plane to the other in an arc from about 90º to 120º (Figure 5.1), and scan lines are collected one after the other as the aircraft moves forward (Lillesand and Kiefer, 2000). At any instant the scanner detects energy in the system's instantaneous field of view (IFOV), and all energy in the IFOV at any instant contributes to the detector response (Lillesand and Kiefer, 2000). This means that if more than one land cover type is sensed, then a 'mixed pixel' will occur, and this means that any image will be made up of 'pure' pixels where only one landcover type has been sensed and 'mixed' pixels where two or more types of cover have been sensed

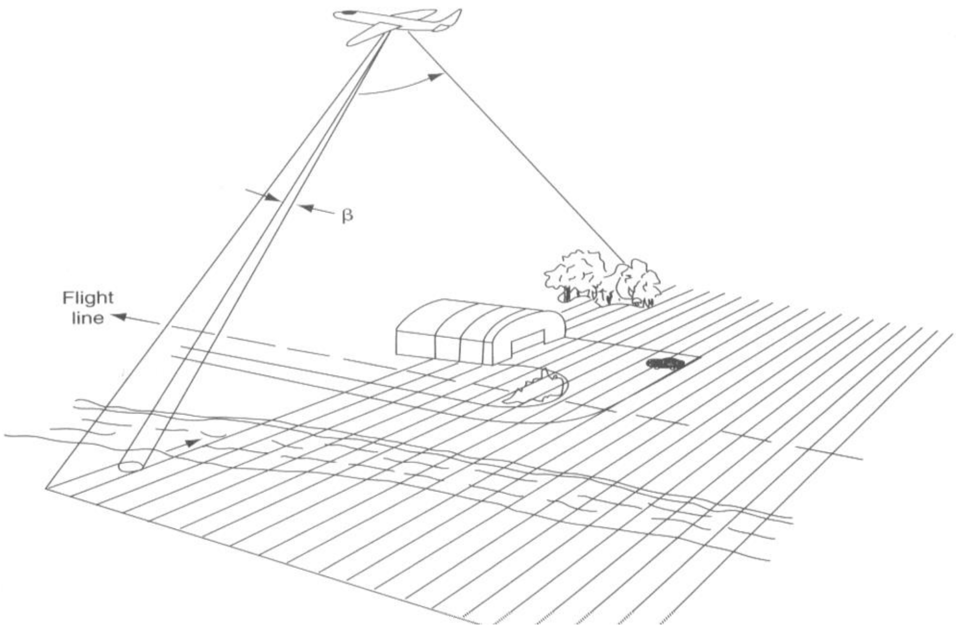


Figure 5.1 The whiskbroom scanner system operation (from Lillesand and Kiefer, 2000)

The field of view of the Daedalus ATM is 90º and its IFOV is 2.5 mrads. The ground spatial resolution (pixel size) of the ATM produced image is defined by these optical characteristics of the scan head and the aircraft altitude. Pixel length and width are defined by the 2.5mrad IFOV, but ground dimensions differ as a function of scan angle from the nadir (Wilson, 1995).

The Daedalus ATM scanner provides 11 spectral channels. These cover the visible and near-infrared (NIR) (channels 1-8), short-wave infrared (SWIR) (channels 9 and 10) and thermal infrared (TIR) (channel 11). This range includes channels that closely match the seven spectral channels of the Landsat Thematic Mapper. Light, captured by the rotating scan mirror is split by filters into a number of light paths which are imaged onto detectors. Visible and near-infrared radiation is split by a prism before being imaged onto an array of silicon detectors (channels 1-8). Middle-(short-wave), and thermal- infrared radiation is split, imaged and recorded on single detector elements held within three individual, liquid nitrogen cooled dewars (channels 9, 10 and 11). The sensor characteristics are listed in Table 5.2 below.

Band	Centre	Width	Start	End	Landsat equivalent	Purpose
1	0.435	0.030	0.420	0.450		Water penetration mapping
2	0.485	0.070	0.450	0.520	1	Water body penetration, soil/vegetation discrimination, forest type mapping and cultural feature identification
3	0.560	0.080	0.520	0.600	2	Measures the green reflectance peak of vegetation for vegetation discrimination and vigour assessment
4	0.615	0.020	0.605	0.625		Water quality, dissolved matter
5	0.660	0.060	0.630	0.690	3	Senses in a chlorophyll absorption region for aiding plant species discrimination
6	0.7225	0.055	0.695	0.750		Vegetation red edge curve
7	0.830	0.140	0.760	0.900	4	Vegetation maximum reflectance. Useful for determining vegetation types, vigour and biomass content, for delineating water bodies and soil moisture discrimination
8	0.980	0.140	0.910	1.050		NIR including water absorption
9	1.650	0.200	1.550	1.750	5	Indicative of vegetation moisture content and soil moisture. Differentiates snow from clouds.
10	2.215	0.270	2.080	2.350	7	Discriminates between mineral and rock types. Also vegetation moisture content
11	10.750	4.500	8.500	13.00	6	Thermal IR, useful for vegetation stress analysis, soil moisture discrimination and thermal mapping applications.

Table 5.2 Daedalus ATM bandset with explanation for purpose of use of each band (Wilson, 1995 with added information from Lillesand and Kiefer, 2000)

5.4.1.1 Flightline parameters and timing

Flightlines for ATM and aerial photograph capture on a NERC campaign are usually drawn up by the user onto 1:50 000 or larger scale maps. The directions for flightlines need to be chosen with care to prevent as much as possible atmospheric distortions which occur especially when flying perpendicular to the solar azimuth. Generally it is best to fly towards or away from the sun to reduce the distortions to a minimum (Wilson, 1995). The 1996 NERC flight over the field area in the Sorbas basin took place on an east to west heading which unfortunately flew almost perpendicular to the sun which would have been in the south east at the time the flight was undertaken which was 10:34am (GMT).

Timing of flights should take into account the position of the sun to enable the correct positioning of the flightline towards or away from the sun. A flight taken in mid morning would need to fly in a SE-NW direction to avoid glare and atmospheric distortions. Early morning or late afternoon flights will be done in a low sun angle which causes long shadows and therefore enhancement of topographic features and reduction in differentiation between shadow and vegetation cover. Most flights are not carried out to discover topographical features and therefore are generally done within 2 hours before or after solar noon. This gives high sun angles, reduction of shadow effects and atmospheric scattering, and provides maximum light for data acquisition (Wilson, 1995).

5.4.2 Processing and extraction of ATM data acquired from the NERC 1996 overflight of the Sorbas Basin

The ATM data was received from NERC in a semi-processed state as an AZSPS.hdf file. It had been processed by NERC to what is known as level 1b which is raw sensor data which has been reformatted to image files with ancillary files appended. This reformatted data then has radiometric calibration applied to produce radiance or irradiance and to which location and navigational information has been appended (Wilson, 1995). A program, Gcorr was supplied with the ATM data. Gcorr was used for geocorrecting the extracted data to take it up to level 3a which is level 1b data mapped to a geographic co-ordinate system using on-board attitude and positional information. This information had been collected by the on-board GPS system used with the Daedalus ATM during the NERC flight. Gcorr allowed correction of the data using projection information, and used a DEM to provide height and topographic information. The file produced by Gcorr was then extracted by another program called EXHDF (extract.hdf). The extracted image file was in a simple BIL (band interleaved by line) file format. This was imported into a remote sensing software package (ERDAS Imagine 8.3), so that it could be aligned in real space by applying map co-ordinates to the top left hand corner of the image and defining the numbers of rows and columns and the pixel size. The image was then in a grid system and map co-ordinates could be displayed rather than file co-ordinates (i.e. map references rather than file references starting with 0,0 at the top left hand corner).

The image swath had pixels in a geographically correct position along the central flightline, but distortion in pixel position increased towards the edges of the swath. This problem was solved to some extent by iterating height figures input into Gcorr. It appears that the GPS height reading recorded during the flight was incorrect as changing the height figures input into Gcorr improved the geopositioning of the image. However, there was still a discrepancy between the ATM image, a georeferenced map and the rectified aerial photograph. To solve this problem, the ATM data was rectified using polynomial rectification within ERDAS Imagine to make the image conform to a map co-ordinate system.

5.5 Investigation of vegetation in the field area using remotely sensed imagery

5.5.1 Cover investigation using the aerial photographs

The study site comprises a larger section of the Barranco del Infierno catchment than the Barranco del Mocatán catchment[3]. On first visual inspection of the unrectified aerial photograph of the study area there appear to be three different types of terrain (Figure 5.2). In the south of the aerial photograph, the landscape appears to have a fairly homogenous dense vegetation cover, interspersed with occasional white or yellow coloured bare terraces (Figure 5.2 at 1). In the north east of the image, in the Barranco del Infierno catchment, there are orange coloured areas which do not appear to have much plant cover interspersed with dark green linear features which are densely vegetated areas (Figure 5.2 at 2). There are areas of badlands abutting channel of the Barranco de los Contreras, a tributary of the Barranco del Infierno (Figure 5.2 at 3) and a few terraced areas in the north. In the Barranco del Mocatán catchment in the north-west of the image (Figure 5.2 at 4) more heterogeneous landcover appears chaotic with a mixture of dark vegetation patches, lighter patches of sparse vegetation or bare ground and a large number of agricultural terraces consisting of a yellow material, some with olive trees visible. A white, gypsum covered road follows the line of the watershed in the northern third of the image and then descends into the Infierno catchment.

The main stream channels have been picked out in blue in Figure 5.2. The Barranco del Mocatán drains in a SSW-NNE direction having its source in the hills to the south of the study area. The Barranco del Infierno has its source in the Malaguica area in the north of the image. It is joined by a tributary, the Barranco de los Contreras in the east of the image (also shown on the topographic map in Fig. 5.3 at 1). The Los Contreras tributary drains in a south-north direction from the south of the field area until just after it is crossed by the gypsum covered track, and it then turns to drain in a SW-NE direction (see Figure5.3 at 2).

[3] Note that 'Infierno catchment' is used to describe the stream valley in the east of the field area. This comprises the Barranco Infierno tributary in the north of the study area and the Barranco de Los Contreras in the south and east.

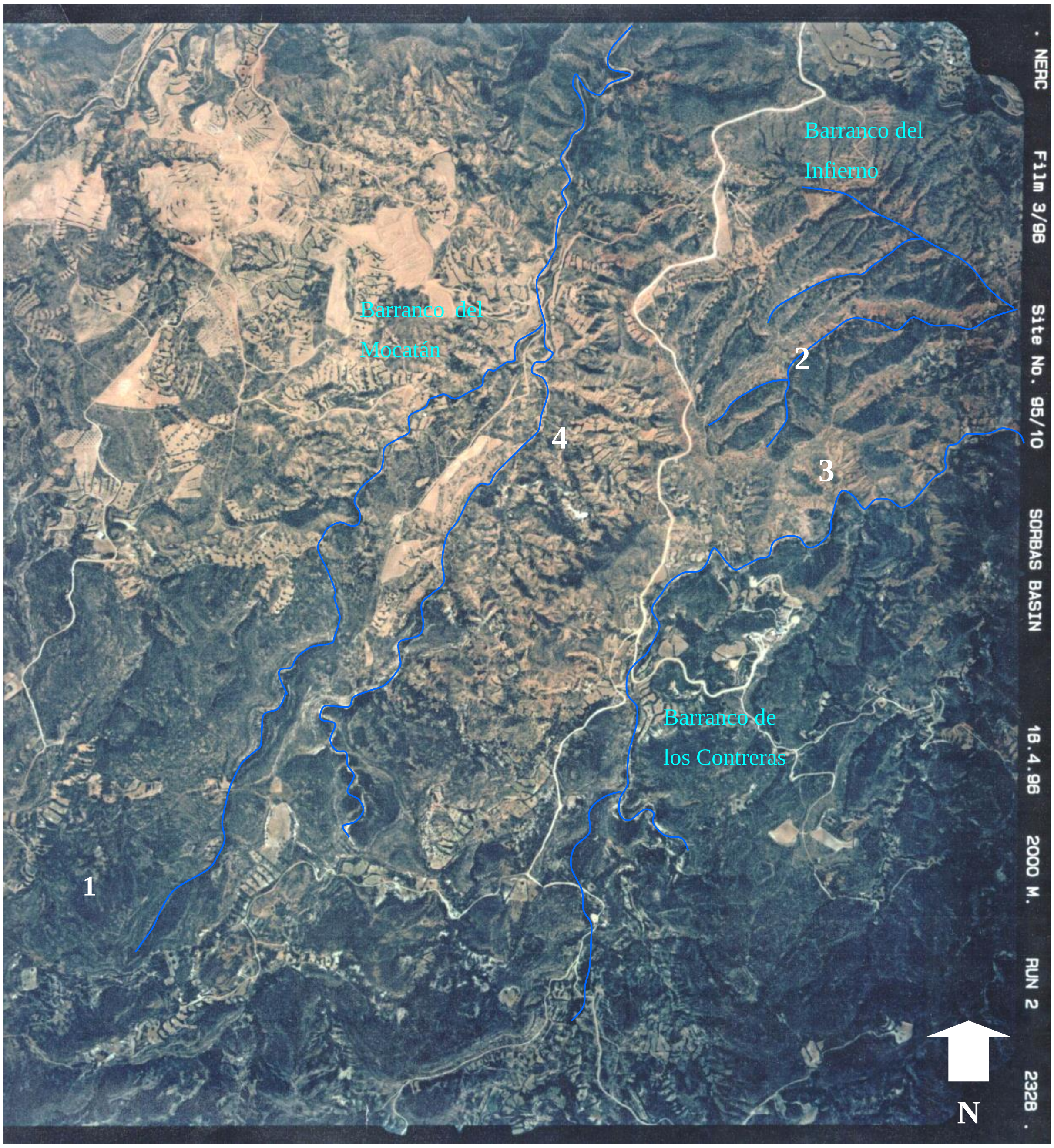


Figure 5.2 Unrectified aerial photograph of the study area (numbers refer to points in the text)

Figure 5.3 Topographic map of the study area (copy of figure 2.13). Numbers refer to points in the text of this chapter.

On examination of the image it is possible to see that vegetation follows the stream channels of the Barranco del Infierno in the north, however, this does not seem to be the case along most of the river channels in the rest of the image. Even in the southern, more densely vegetated area, many of the stream channels of the Barranco de los Contreras show up as the underlying white sediment is visible. This cursory investigation of the field area landscape using an aerial photograph indicates that there are obvious differences in the landcover of the catchments being investigated. From these differences, it can be inferred that different process are operating on the catchments and also on the different geologies present.

One of the first steps taken towards investigating the field area was the production of a hand coloured overlay of the unrectified aerial photograph. This image was produced by laying an acetate sheet over a stereopair of aerial photographs and using a stereoscope to show the area of interest in 3D. The cover observed in this way was transcribed onto the acetate sheet which has been scanned and is shown in figure 5.4.

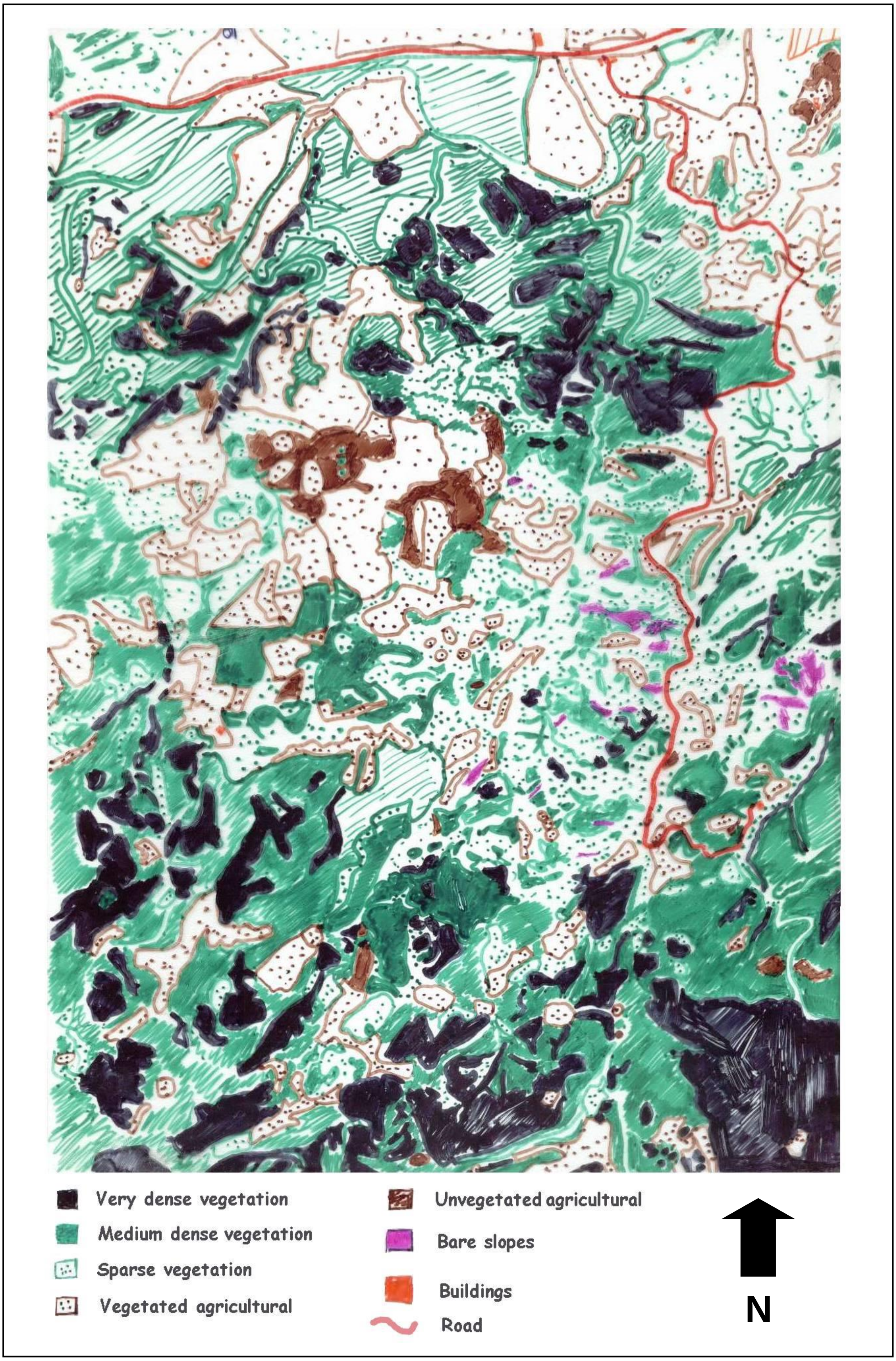


Figure 5.4 Hand coloured acetate overlay of the Mocatán side of the study area

Unfortunately the overlay was only produced for the Mocatán catchment as in the early stages of the thesis, this was the only area being considered. This hand coloured sheet was used as the basis for identifying areas to sample in the field. Areas of known ground cover, for example the gypsum surfaced road and obvious terraces could be identified and so discounted before sampling took place. This stratified random technique, as explained in Chapter 3 enabled a more efficient sampling strategy to be applied, meaning that it was possible to get more information collected in the short period of time provided for sampling.

5.5.2 Ground truthing for ATM data

The ATM data did not become available for investigation until after the first two field seasons were completed in April and May 1997 and 1998. Hence the selection of sites for ground truthing prior to the ATM data arrival relied upon visual interpretation of the aerial photographs. The choice of size and location of training areas was determined by the need for homogenous ground truth data for ATM interpretation. Methods of site selection and data collection are discussed in full in Chapter 3 section 3.3. The positions of the training areas collected during the 1997 and 1998 field seasons were found using a handheld Trimble GPS, with readings taken at the north-east or northern corner of each (depending on the orientation of the training area). These GPS readings were corrected in Pathfinder Office using data from the GPS base station at the Polytechnic University of Madrid. A vector layer containing the 42 15x15m training areas was created in ERDAS Imagine, using the GPS referenced points as starting vertices, after the spring 1997 fieldwork. (Figure 5.5). This vector layer could then be displayed over the already georeferenced aerial photographs. Field work was carried out in September 1997 to ensure that the spring 1997 training areas had been correctly placed on the aerial photographs, and so confirm the accuracy of the georeferencing of the aerial photographs. The positions of the 25 training areas surveyed in 1998 were added to the 1997 positions to produce a vector layer showing all 65 15x15m training areas (Figure 5.5).

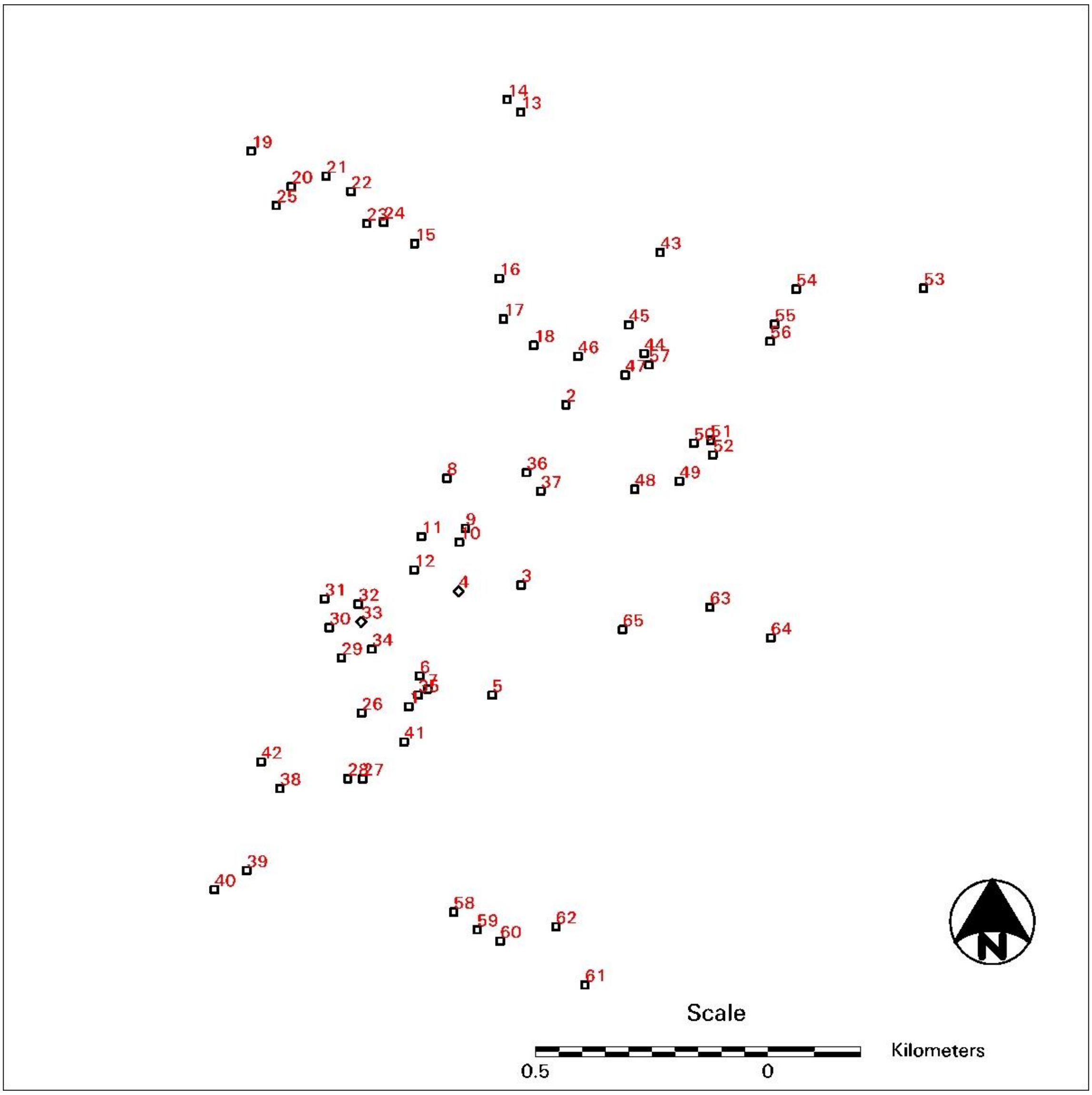


Figure 5.5 Distribution of training areas from 1997 and 1998 field work (1997 1-42, 1998 43-65)

5.5.3 Creation of an NDVI image

When the ATM data arrived and after initial processing as described in section 5.4.2, an NDVI equation (Section 5.2.1.2) was run in ERDAS Imagine to produce an image that classifies according to the amount of green plant tissue. This image was created by modifying one of ERDAS Imagine's models. The model was created for use with Landsat TM bands 3 and 4, and was modified to work with the ATM bands 5 and 7. This image is reproduced in Figure 5.6. The areas which are lightest in colour on the NDVI image are those which have the greatest concentration of green plant tissue.

NDVI was chosen as opposed to SAVI or any other vegetation index to investigate the field area. The reason for this is that the NDVI is the most commonly used vegetation index (Ray, 1994), and there is a large body of literature supporting the use of NDVI as a technique for identifying vegetation from remotely sensed sources. It is acknowledged that SAVI is useful for identifying vegetation in landscapes where there is between 15% and 30% cover. However, the study area is extremely heterogeneous in its cover with some areas having very low vegetation cover – notably the modern agricultural terraces, and some others having almost continuous cover. SAVI would be useful for identifying vegetation in the areas of low cover, but it is already known that these large areas of sparse vegetation are mostly terraces, and hence the land cover is known. It is the areas with intermediate cover that are of most interest and it was thought that NDVI would produce the best results. As comparison, an SAVI image was created by modifying an ERDAS Imagine model to fit the correct Daedalus ATM bands. The two vegetation indices images were compared, and the SAVI was found to be very similar to the NDVI image. It was decided to continue with the NDVI image for landscape investigation.

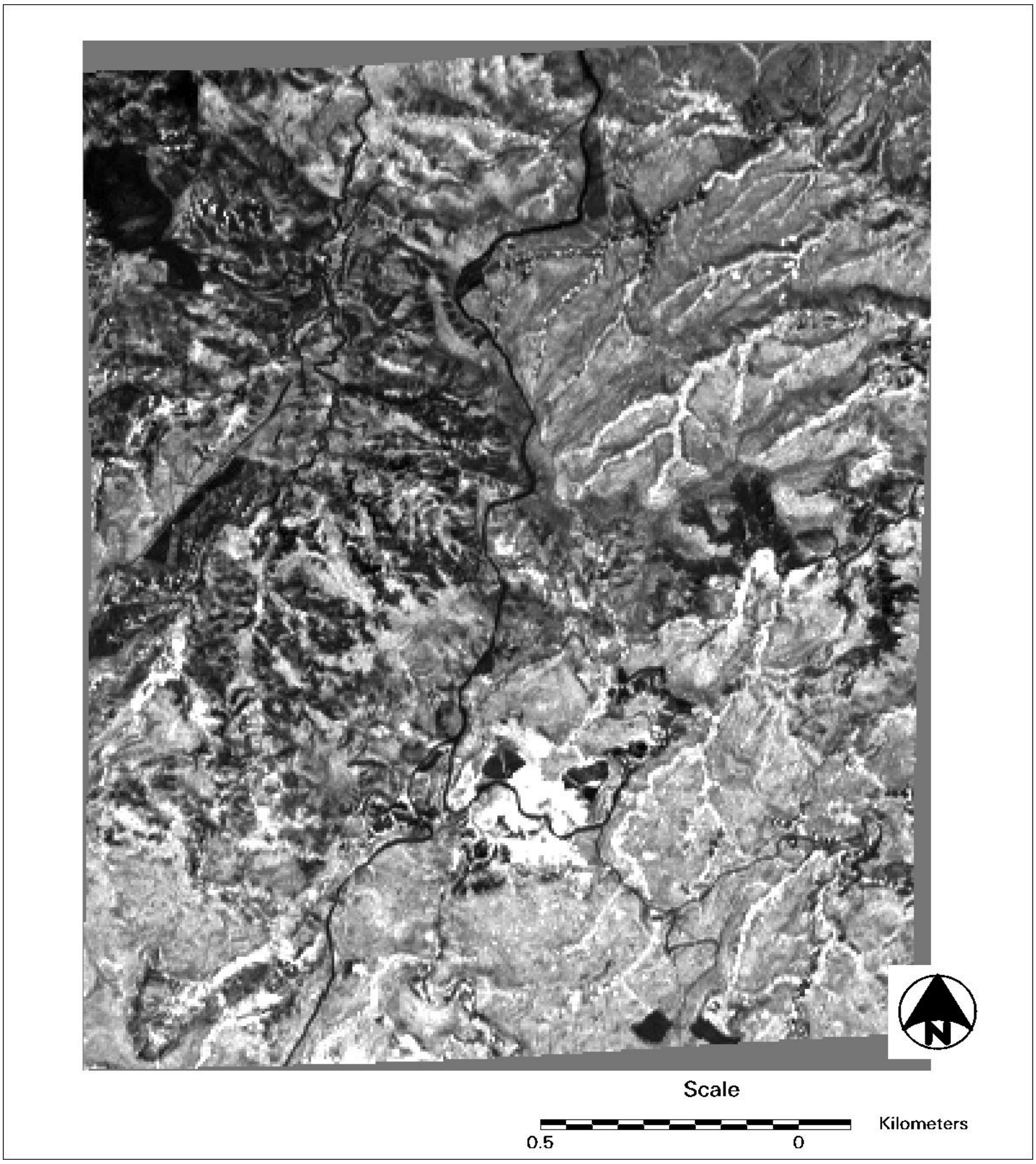


Figure 5.6 NDVI image of the study area

5.5.4 Clustering of the NDVI image

The NDVI image, although highlighting areas with the highest concentration of green plant tissue, was not the right tool for the exploration of patchiness of ground cover in the study area as it contained too much information presented in its raw form. The data contained within the image would be easier to investigate if it were simplified. The method of simplification of the data chosen was unsupervised (as opposed to supervised) classification. Unsupervised classification involves algorithms which examine unknown pixels in an image and aggregate them into a number of classes based on the natural groupings or clusters present in the image values. These groupings are spectral classes and are based solely on the natural groupings in the image values – the identity of these classes then has to be determined by investigation of areas of each class in the field. Unsupervised classification determines spectrally separable classes which then have their informational utility defined by the user (Lillesand and Kiefer, 2000). Unsupervised classification involves little initial input from the user, unlike supervised classification where input of signatures is needed to select areas of a recognised land cover. This selection of training signatures can be inaccurate if areas of overlapping spectral characteristics are chosen which would mean the resulting output of a classified image would be incorrect The input of signatures to a supervised classification needs to be accurate to represent the categories originally identified within the data (ERDAS, 1999). Unsupervised classification, although initially simple to run, needs to be interpreted which means that the work needs to be done after the classification to analyse the resulting image and its respective classes in conjunction with data from the landscape being classified. Unsupervised classification carried out on a one-band image as opposed to a multi-band image is known as clustering rather than classification.

Clustering of the NDVI image was run using the Iterative Self-Organising Data Analysis Technique (ISODATA) found within ERDAS Imagine to cluster together areas of the image which are similar. This clustering method uses spectral distances and iteratively classifies the pixels, redefines the class criteria and then classifies again. It clustered together pixels within ranges of NDVI which were arbitrarily chosen by the algorithm. Spectral distance patterns emerge during the clustering process (ERDAS, 1999). These pixel clusters were termed ‘classes’ and this term is used throughout the rest of the thesis. The classes produced by the clustering could then be examined, along with training area data and knowledge of the field area to see whether the classes produced by the clustering made sense of the landscape of the field area. ISODATA within ERDAS Imagine was used to produce a series of clustered images with 2, 4, 6 and 8 classes which are discussed in Chapter 6 (Figures 6.1, 6.2, 6.3, 6.5). The 65 1997 and 1998 15x15m training areas were then overlaid onto these clustered NDVI images and the amount of each class that the training area contained was measured for each of the four images produced. This was done to see how well the training areas fit the classification bearing in mind that the training areas were selected in the field as ‘homogenous areas’. The measurement was done using the ERDAS Imagine measure tool (see Figure5.7) which allowed the area of each of the blocks of different cover types contained within a training area to be delineated. These values were then divided by the total area of each training area to give the percentage of the training area covered by each type of clustered cover. This process was carried out for all four clustered images and the tables of results are given in Appendix 4.

The area of each pixel or part of a pixel of the clustered NDVI image falling within the boundary of a training area had to be measured. The pixels could not simply be counted, as, although the training areas had been big enough to encompass nine pixels at 5m resolution, the training areas generally did not fit precisely around nine individual pixels. The training areas could contain sections of up to 16 pixels (Figure 5.7).

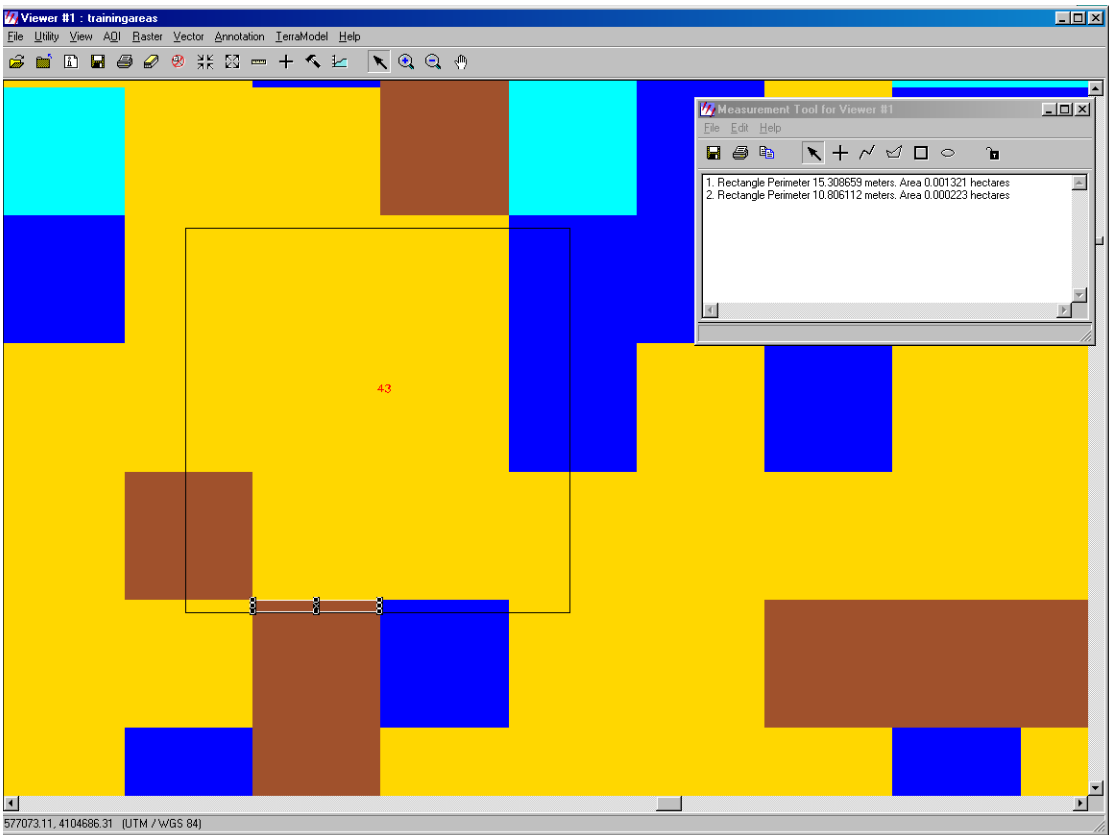


Figure 5.7 Screen dump from ERDAS Imagine showing the measure tool being used to find the areas of sections of pixels of the same class within a training area

The results of overlaying the training areas onto the four clustered NDVI images showed that the NDVI clusterings generally displayed heterogeneity within the training areas, which had been assessed as homogeneous in the field. Even in the two class NDVI image, only 15 out of 65 contained 100% of one or other class. However as discussed in Chapter 3 there was some difficulty finding places where the cover was sufficiently homogenous to lay out 15x15m training areas. It would seem likely therefore that the problems did not lie just with the classification, but also with the collection of data in the field. Even with the mismatch of training areas to single NDVI classes, it was possible to use the data collected in the training areas together with a knowledge of ground cover, to interpret the classes in the NDVI images. The interpretation of the NDVI images is discussed in Chapter 6.

One process that was not carried out before production of the NDVI image was that of shadow removal. Shadow removal or topographic normalisation is the process of removing the effect of shadow from an image which causes a darkening effect on areas that are shaded. A shadow removal operation involves the input of solar elevation and azimuth at the time of image acquisition, a DEM of the area for shadow removal and the original image (ERDAS, 1999). This process was omitted until after the data had been processed, an NDVI image created and initial analysis with overlaying training areas done. To test whether shadow removal would make a difference, a shadow removed image was created, and an NDVI image was created from this. The shadow removed NDVI image was clustered into six classes in the same way that the original NDVI was clustered into six classes. A comparison of the image statistics was run to identify if there was a large difference between the two images and the results are reported in percentages in Table 5.3 This is to overcome the differences in pixel size. The shadow removal created an image with a 2m resolution due to the use of the 2m resolution DEM.

Class	Original six class NDVI image %	Shadow removed six class NDVI image %	Difference (shadow-non-shadow) %
1	14.55	14.52	0.03
2	17.86	17.86	0.00
3	23.51	23.69	-0.18
4	18.01	17.98	0.03
5	20.28	20.17	0.10
6	5.80	5.78	0.02

Table 5.3 Comparing pixel percentages in each class in the original and shadow removed images.

The results of the investigation into shadow removal from the NDVI image indicates that there are small differences between the shadow and shadow removed images, the biggest being that of class 3 with a 0.18% increase in class 3 pixels. This is partly to do with an increase in class 3 due to higher classes being downgraded to class 3 by the shadow removal process, however a flaw in the image created by the edge of the DEM being superimposed on the shadow removed image and clustered as class 3. This is likely to account for the change in the amount of class 1. However, the 0.1% drop in class 5 pixels is most probably attributable to these pixels being downgraded to class 3 in the shadow removed image. Thus, there was a difference between the image with the shadow removed and the image without shadow removal, but it made a small difference overall to the clustered NDVI image. As work had already been carried out on the non-shadow removed image, it was decided to continue with the original image. The consequence of this is that an awareness of the effect of aspect on the appearance of the cover needed to be taken into account, although the effect was small.

5.6 Summary

11 band ATM data from NERC was processed to produce a georeferenced image. This image was subset to the size of the study area. NDVI was chosen as the best remote sensing method for investigating vegetation in the field area. An NDVI image was computed using the standard NDVI equation and using bands 5 and 7 from the ATM image. Clustering was used to simplify the NDVI

image, producing four clustered images with two, four six and eight classes to investigate with reference to the training areas collected in the field in 1997 and 1998.

6 CHOICE AND INVESTIGATION OF THE CLUSTERED NDVI IMAGE

6.1 Introduction

Chapter 6 demonstrates the process of choosing the clustered NDVI image which was used for investigation of the landscape. As discussed in Chapter 5, four clustered NDVI images were produced with two, four, six and eight classes respectively. A choice needed to be made to use one of these images for landscape interpretation with the environmental variables aspect, slope and wetness as described in Chapter 4. The process of selecting the best clustered image for the purpose of landscape investigation is described in section 6.2. An investigation of the chosen clustered NDVI image and slope, aspect and wetness is given in section 6.3.

6.2 Interpretation of the four clustered NDVI images

The four clustered NDVI images which were created as discussed in Chapter 5 were interpreted using the training areas collected in the field in 1997 and 1998 as discussed in Chapter 3, rectified aerial photograph, topographic maps and knowledge of the field area.

6.2.1 Two class NDVI image – discussion of classes

In the two-class NDVI image (fig 6.1) it can be shown that class 1 corresponds to bare ground or sparsely vegetated land cover and class 2 to more densely vegetated land cover. Using the geolink function in ERDAS Imagine, it was possible to look at the rectified aerial photograph of the area, and the two class NDVI image side by side and zoom to the same area in both images. Class 1 picks out, for example, areas of bare terraces, eroded areas and the white gypsum-covered road in both catchments. Class 2 picks out more heavily vegetated areas such as the densely covered area of Sorbas member sediment in the south of the image, the areas of dense vegetation on the ridge tops in the Mocatán catchment and in the valley bottoms within the Infierno catchment.

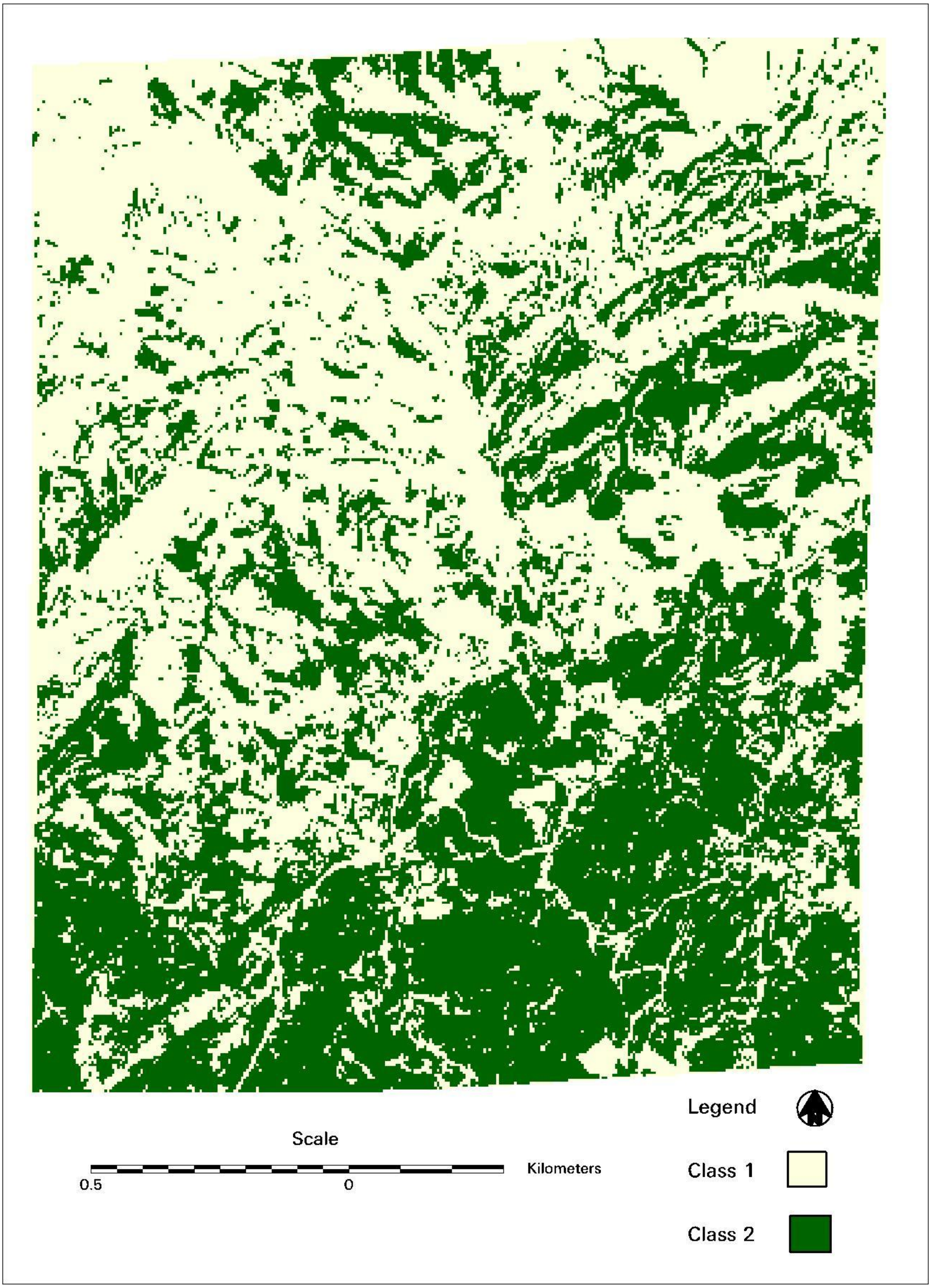


Figure 6.1 Two class NDVI image

6.2.2 Four class NDVI image – discussion of classes

The four class NDVI Image (Figure 6.2) appears to sub-divide the two original classes from Figure 6.1. Class 1 shows the very bare areas, those which appear to be a landcover type of the lightest, whitest sediment. This is more predominant in the Mocatán catchment reflecting the large bare agricultural fields in the north and west of the field area and the badlands towards the centre of the image. Class 1 also picks out the area of badlands in the Barranco de los Contreras which are bare (Figure 6.2 at 1).

Class 2 is more predominant in the Malaguica area of the field site, where it forms coherent blocks of cover (Figure 6.2 at 2), than in the southern part of the Infierno catchment and the Mocatán catchment. In the latter areas class 2 forms a rim around larger areas of class 1. Class 2 appears to be associated with those areas that have moderately sparse vegetation cover. Class 3 forms small patches of cover in the Mocatán catchment, and becomes very sparse in the north west and centre of this area. There are larger areas of class 3 in the north and south of the Mocatán catchment. Class 3 is much more in evidence in the Infierno catchment where it forms larger blocks of cover, especially in the south. Class 3 appears to be associated with areas of moderately dense vegetation when looking at the aerial photograph of the catchments.

The northern Mocatán catchment has little class 4, and what class 4 can be found there is fragmented into very small patches, almost always surrounded by class 3. There is more class 4 in the middle and south of the Mocatán catchment. In the middle area it is associated with the tops of ridges that run SE-NW from Cerro de Juan Contreras, and can be found on the ridge tops (Figure 6.2 at 3). These areas of class 4 are also surrounded by class 3 in most cases. In the Infierno catchment there are large patches of class 4 to be found on areas underlain by the Sorbas member, and also linear patches of class 4 to be found in the valley bottoms of both the Barranco del Infierno and the Barranco de los Contreras where it is again associated with a rim of class 3. Class 4 appears from investigation of the aerial photograph to contain the most dense vegetation in the field area.

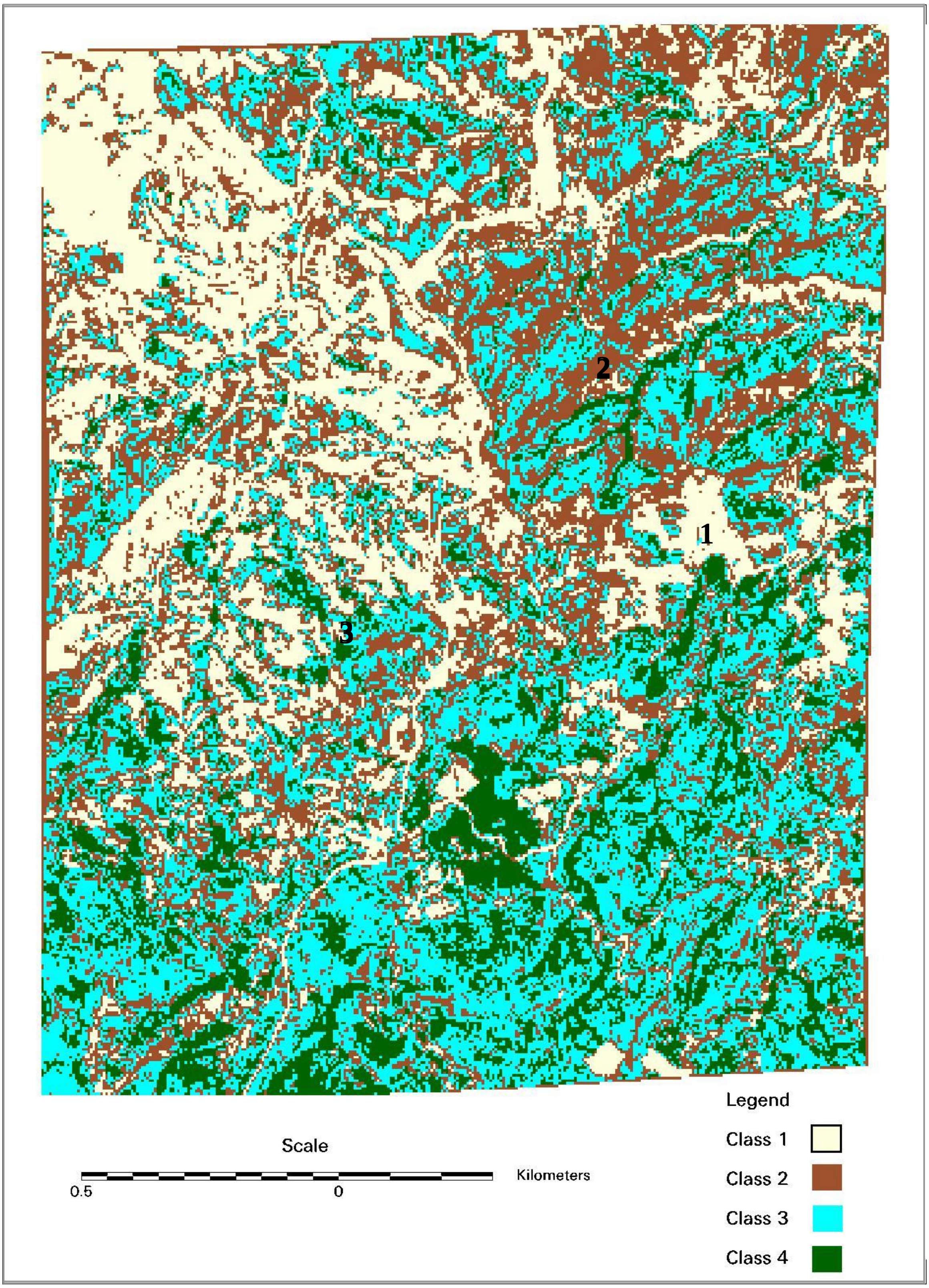


Figure 6.2 Four class NDVI image

6.2.3 Six class NDVI image – discussion of classes

6.2.3.1 Class 1

Class 1 is found throughout the centre and north of the Mocatán catchment. On the north west side of the Barranco del Mocatán, class 1 is mainly indicative of large, bare ploughed fields and terraces. In the centre of the image, along the barranco its-self and to its east class 1 indicates some of the most bare, eroded areas with piping and gullying, There are a few areas in the centre and south of the image where class 1 intrudes directly into classes 5 and 6. There is little class 1 on the Sorbas member in the Mocatán catchment. Class 1 is not a common cover type in the Infierno catchment. Where it is found, it is generally on bare fields along the road side. The only place in this catchment where there are large patches of this cover type is where there are significant badland areas on the north side of the Barranco de los Contreras which are associated with the Triassic Rich Unit (TRU) (Mather 1993 Figure 6.3) which is the same material as found in the northern Mocatán catchment. As in the Mocatán catchment, class 1 is hardly found at all on the Sorbas member geology in the Infierno catchment (Figure 6.4).

6.2.3.2 Class 2

Class 2 generally surrounds patches of class 1 in the north and central part of the Mocatán catchment study area (Figure 6.4). It can also be found associated with some class 3 in the north of the field area on part of the Messinian Rich Unit (MRU) that extends into the Mocatán catchment (Mather, 1993; Mather and Stokes, 1996). A map showing the extent of the two units can be found in Figure 6.3. When compared to the aerial photograph, class 2 appears to describe areas with a sparse covering of vegetation, and a lot of sediment showing through. In the north of the Infierno catchment class 2 appears in much larger patches than in the Mocatán catchment. Class 2 appears to describe bare areas of the darker MRU as well as some lighter areas which have a visible scattering of vegetation. There is little class 2 on the Sorbas member material in either the Infierno or Mocatán catchments. Where class 2 does appear it is along the tracks or where terraces have been recently ploughed.

6.2.3.3 Class 3

Class 3 is extremely scattered in the Mocatán catchment. It does not form large patches in many places. Comparing the NDVI image to the aerial photograph it can be seen that class 3 is more heavily vegetated than classes one and two, but there is still obviously sediment showing through. There are larger patches of class 3 on the MRU that extends into the north of the Mocatán catchment. The north of the Infierno catchment contains large patches of class 3 and it appears to be one of the more common landcover types. Comparison to the aerial photograph shows that class 3 areas have a covering of vegetation, but again as in Mocatán, there is still some sediment to be seen showing through the layer of vegetation. There are a few patches of class 3 on the Sorbas sediment in the south of the Mocatán and Infierno catchments. These appear to be associated with class 2 and appear to represent areas of disturbed or cultivated land.

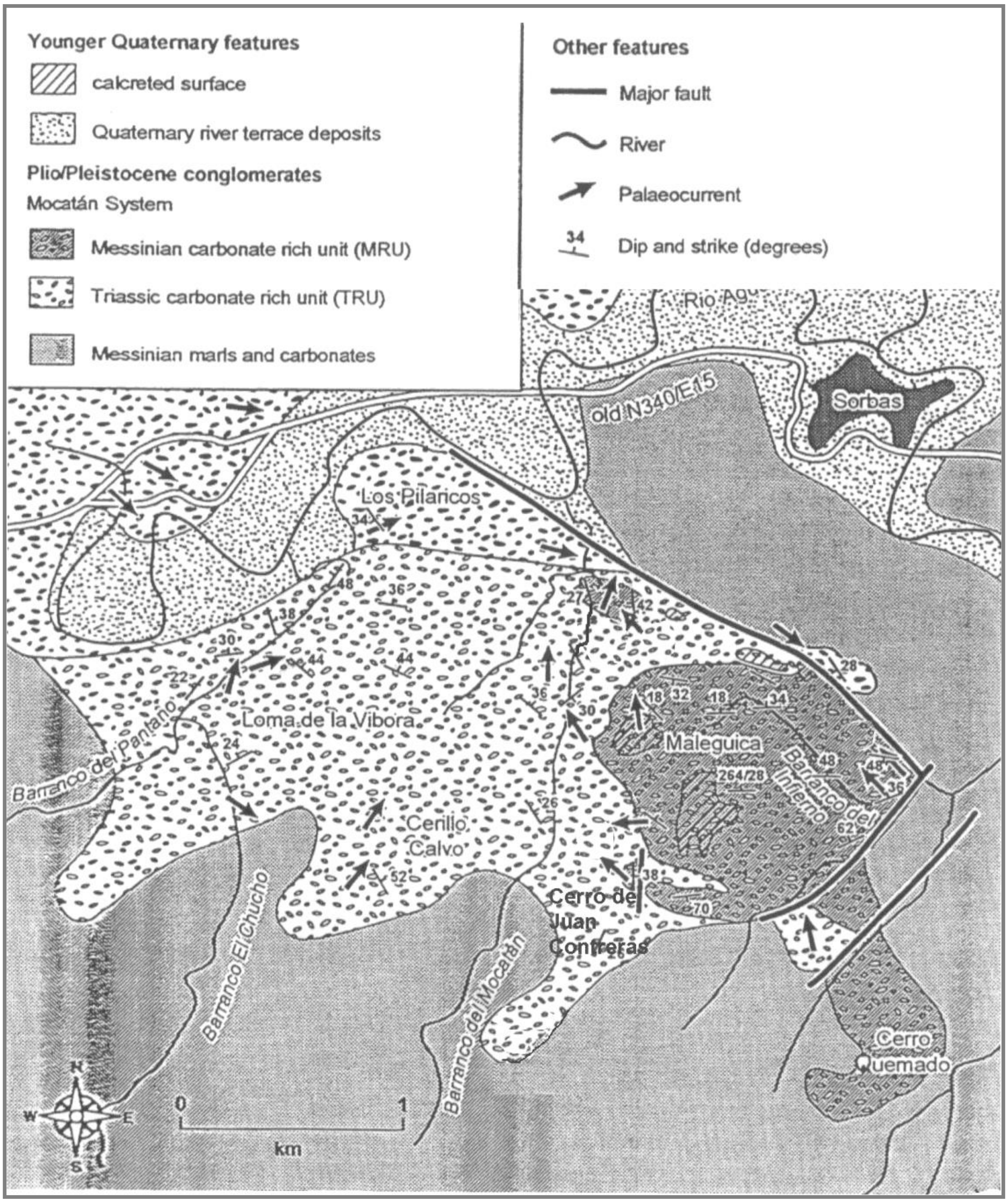


Figure 6.3 MRU and TRU geology in the study area (adapted from Mather and Stokes, 1996)

6.2.3.4 Class 4

In the far north of the Mocatán catchment, class 4 is relatively common on the MRU sediment where it surrounds patches of class 5. It is rarely found unassociated with class 5 in this area. On the aerial photograph class 4 seems to be a fairly dense cover of vegetation with little, if any sediment showing through. There are scattered areas of class 4 in the north-west of the Mocatán catchment, but they are very small, which is understandable as this area is mainly composed of bare agricultural terraces. Towards the centre of the Mocatán catchment, class 4 becomes more common, but it is still very fragmented. Where is occurs it is often found surrounding or next to equally small areas of class 5. Class 4 becomes more common on the top and north side of Cerro de Juan Contreras, and on the sides of the ridges that run north-west from the main body of the hill. These areas appear to have medium dense vegetation cover on the aerial photograph, with some sediment visible through the vegetation.

There are large patches of class 4 in the north of the Infierno catchment in the Malaguica area which are more associated with class 3 as well as the more usual association of class 4 with class 5. The class 4 areas which are associated with class 5 areas can be found in the valley bottoms and on the north sides of the ridges. Class 4 is less common around the badland area on the north side of the Barranco de los Contreras, but can be found surrounding class 5 areas on the south side of the Barranco where the geology changes to the Sorbas member. The field area on the Sorbas sediment contains a lot of class 4 surrounding class 5. Class 4 on Sorbas material shows, in the aerial photograph, a covering of medium dense vegetation through which some of the sediment can be seen.

6.2.3.5 Class 5

In the north of the Mocatán catchment on the MRU material, class 5 can be found in the small tributary valleys leading down to the barranco. Class 5 sometimes surrounds very small areas of class 6. In the north-west of the catchment there is very little class 5. In the badland area towards the centre of the catchment, the ridges from Cerro de Juan Contreras have a cover of class 5, occasionally surrounding a much smaller area of class 6. In the west of the catchment area, the Barranco del Mocatán and several of its tributaries actually contain some class 5 cover, again occasionally surrounding some class 6. This is likely to be associated with the springs and standing water that can be found here. Class 5 areas on the aerial photograph appear as dark green, plant-covered surfaces. There is little or no sediment visible through the green.

In the Malaguica area of the Infierno catchment in the north, class 5 is not as common as 3 and 4. Class 5 occurs on the valley floors and up the sides of some of the north facing ridges. On the aerial photograph, the cover appears to be dense vegetation, but unlike in the Mocatán catchment, there is occasionally sediment showing through. To the south, on the Sorbas member in both catchments class 5 appears to be the most prevalent land cover type. It has scattered blocks of class 6 within it and is surrounded by class 4 in some places. On the aerial photograph, this area appears to have a medium dense cover of vegetation with sediment occasionally showing through

6.2.3.6 Class 6

Class 6 has the smallest amount of cover in both the catchments. It is always found surrounded by or next to class 5. In the northern Mocatán catchment, there is a little class 6 in the tributary bottoms, surrounded by class 5. In the north-west of the catchment there are tiny fragments of class 6, again surrounded by class 5. These fragments amount to little more than patches of one or two pixels (5x5m or 5x10m). In the centre of the Mocatán catchment, there is more class 6 than in the north-west. It is particularly associated with stream channels and areas of class 5 that run along them. There is class 6 to be found on the north-west facing side of Cerro de Juan Contreras, and further down on the ridge tops running north-west from Cerro de Juan Contreras, surrounded by class 5. There is little class 6 to be found in the main badland section of the Mocatán catchment. On the aerial photographs the appearance of class 6 in the Mocatán catchment is a very dark green vegetation cover with no sediment showing through.

The Malaguica area of the Infierno catchment does not contain much class 6. What little there is, is associated with class 5 which adjoins or surrounds it. Class 6 is always found in the valley bottoms; there is none on the ridge tops or sides. The appearance of class 6 on the aerial photograph is very dark green. There is no sediment visible through the vegetation. Further south in the Infierno catchment, there is some class 6 associated with the large amounts of class 5 around the running water in the valley bottom underneath the Barranco de los Contreras badland area.

In both catchments, class 6 is common on the Sorbas sediment. There is a very large homogenous area of class 6 to the east of the fork in the gypsum track (Figure 6.4 at 1). Class 6 also follows tributary valley bottoms in both catchments. Class 6 is associated with class 5 throughout the Sorbas member area. Its appearance on the aerial photograph is very dark green with no sediment showing through.

6.2.4 Eight class clustered NDVI image – discussion of classes

All discussion of classes in this section refer to Figure 6.5

6.2.4.1 Class 1

Class 1 appears to have picked out just the barest, most lightly coloured areas in both catchments. These include the gypsum covered road, the large fields in the north-west of the Mocatán catchment, the Barranco de los Contreras badlands and a few small bare fields on the Sorbas member. There is a lot more class 1 in the Mocatán catchment that in the Infierno catchment Class 1 appears to make coherent patches and is almost always surrounded by class 2.

6.2.4.2 Class 2

Class 2 appears more often in the Mocatán catchment than in the Infierno catchment. It seems to be associated with slightly darker bare material, or material with a scattering of plants on the surface. Class 2 appears always to encircle class 1 where it appears in the Mocatán catchment whereas in the Malaguica area of the Infierno catchment, class 2 appears alone. On the aerial photograph, these areas appear as a red-brown colour, possibly bare ground of the MRU with a very sparse covering of plants. Class 2 is very rarely found on the Sorbas member, but where it does occur, it is associated with roads, erosion and bare terraces.

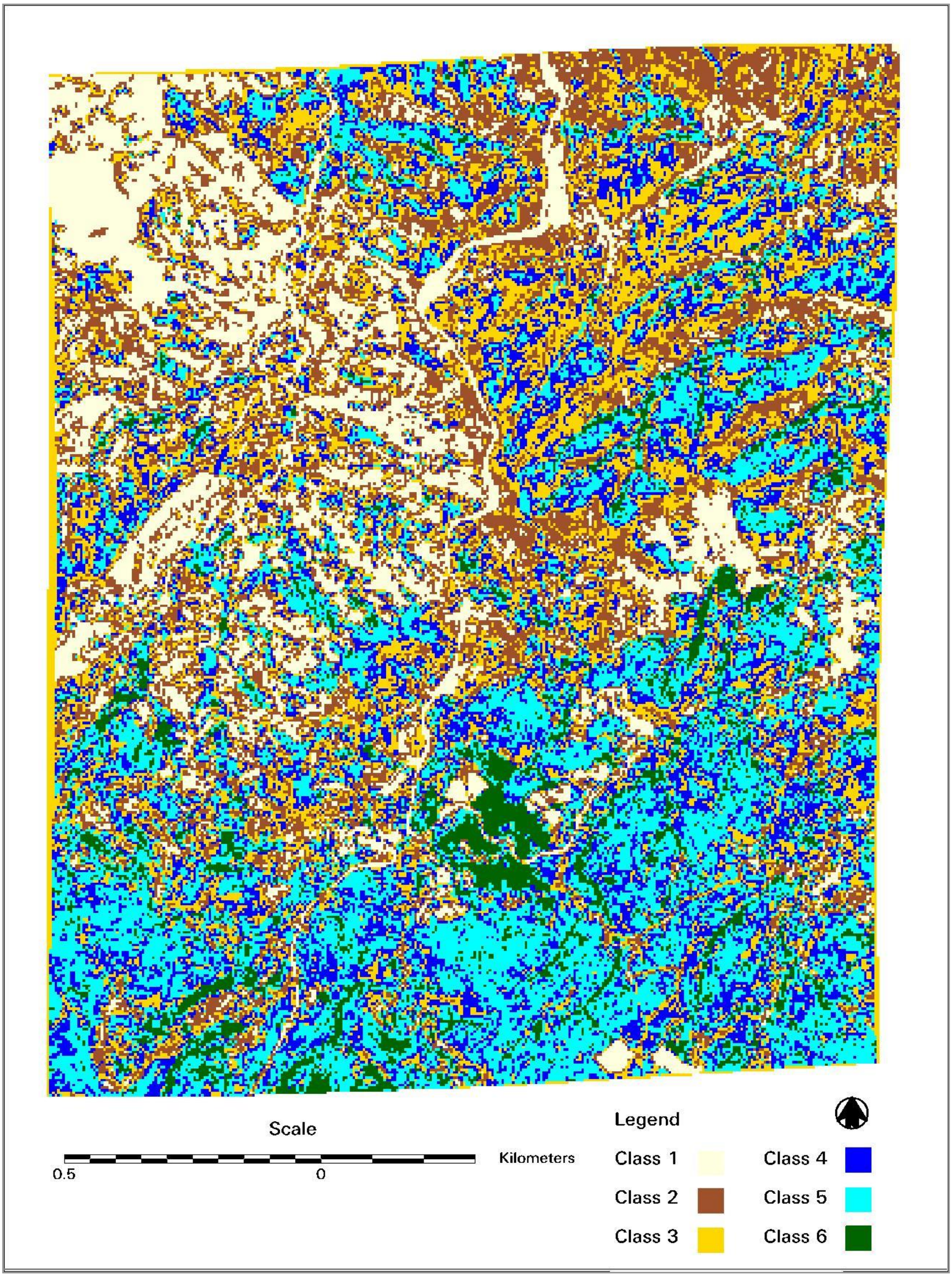


Figure 6.4 Six class NDVI image

6.2.4.3 Classes 3 and 4

Class 3 appears to be frequently associated with class 4, especially in the Malaguica area of the Infierno catchment. There are no large blocks of classes 3 or 4 in the field area. If classes three and four are displayed together, they make up quite large blocks in the Malaguica area where, on the aerial photograph, they appear to represent a sparse cover on the south-east facing slopes of the SW-NE trending ridges. In the Mocatán catchment these classes are very scattered: nowhere forming coherent areas of cover. Class 3 and 4 are found on the Sorbas member in the areas around bare terraces or erosion scars where there is a little sparse vegetation showing with bare sediment visible underneath.

6.2.4.4 Classes 5 and 6

Classes 5 and 6 are both very scattered classes. In the Malaguica area of the Infierno catchment, class 5 is associated either with class 4 or class 6 and describes the denser vegetation on the north-west facing sides of the ridges. In the north-west of the Mocatán catchment, class 5 is very scattered and mixed in with cover classes two, three, four and six. There are very few patches of class 5 bigger than 3x3 pixels. Where it is possible to identify areas of class 5 on the aerial photograph they correspond with medium dense vegetation with a little sediment showing through.

Class 6 forms some patches of cover in the north of the Malaguica area of the Infierno catchment. These patches are generally surrounded by class 5. Further south in the Malaguica area, class 6 is mixed in with both class 7 and class 5 in some of the channel bottoms which are less densely vegetated than other channel bottoms. Class 6 is also associated with north and north-west facing slopes in Malaguica. On the aerial photograph, these areas look densely vegetated, with sediment showing through only occasionally. In the north of the Mocatán catchment on the MRU, classes 5 and 6 surround blocks of class 7. The cover identified on the aerial photograph is medium dense with some sediment showing through. On the Sorbas member, classes 5 and 6 are mostly associated together and again describes medium dense vegetation with some sediment showing through. Classes 5 and 6 surround coherent blocks of class 7 on the Sorbas member areas in both catchments.

6.2.4.5 Classes 7 and 8

Class 7 forms large blocks in both catchments. In the north of the Mocatán catchment on the MRU, there are linear blocks of class 7 in the tributary valleys surrounding smaller blocks of class 8. On the aerial photograph class 7 is a dark green apparently dense cover of vegetation. There is little class 7 in the north-west of the Mocatán catchment, its presence here consisting of a few blocks of two or three pixels in size. In the east of the Mocatán catchment, there are a few blocks of class 7 surrounding smaller areas of class 8 in the tributary valley bottoms where there is standing water. The badlands at the centre of the Mocatán catchment contain a few small areas of class 7 with single pixel patches of class 8 at their centre. There are several large patches of class 7 on the north west facing side of Cerro de Juan Contreras which extend along the ridges to the north-west. These are identified on the aerial photograph as dark green, heavily vegetated areas without any sediment showing through. The small areas of class 8 are slightly darker on the aerial photograph.

There are a few large patches of class 7 with small cores of class 8 in the far north of the Malaguica area in the valley bottoms. Further south the areas of class 7 get larger, and class 8 appears to fill more of the valley bottoms. This is identified on the aerial photograph by very dense vegetation. Below the Barranco de los Contreras badlands there is a large patch of class 8 surrounded by a rim of class 7. Again this appears dark on the aerial photograph. Classes 7 and 8 form the largest patches in the Sorbas member areas in the south of both catchments. These are identified on the aerial photograph as areas of dark green cover with no sediment showing through. Generally the areas of class 8 are darker green than those of class 7. Classes seven and eight can be found on the hilltops and in the valley bottoms.

6.3 Selection of the clustered image for use

One of the clustered NDVI images had to be selected for testing in the field, for use with landscape ecology metrics and for further analysis using field data and GIS functions. The criteria that needed to be met by a clustered image were that the image had to provide useful, verifiable information about the field area. If there were not enough classes, then the classification would not give a clear picture of the different land cover types in the field area. If there were too many classes, this would subdivide apparently very similar land cover types which would lead to sampling problems in the field, and make the output from landscape metrics packages overcomplex leading to the likely loss of an overall picture of the study area. What was needed was an image which showed the heterogeneity of the field area landscape, but also had patches of land cover type that were large enough to carry out meaningful analysis using the landscape metrics software. After examination of the images and the distribution of the classes in the images and comparing them to the aerial photograph of the study area it was decided that the six class classification provided the best information about the study area. The reasons for this are given below.

The two class NDVI image did not provide enough information to be useful in the field or for use with landscape ecology indices. The four class NDVI image could have been used, but it appeared to miss some subtle differences that were more obviously picked out by the six class image. The eight class NDVI image had a complex appearance, and many of the patches were very small, which would have led to problems with the landscape metrics software. The six class NDVI image appeared to work best with the land cover data collected in the field in 1997 and 1998, thus it was the clustered image that was chosen for use. The NDVI class signature boundaries for the six class NDVI image can be found in Appendix 3. Although only just over two thirds of the training areas collected in the 1997 and 1998 field seasons contained more than 50% of a single class, the detailed cover data could be used to describe the six classes and the type of cover that was represented by each. This was done and the class definitions were tested in the field during the spring 2000 field season.

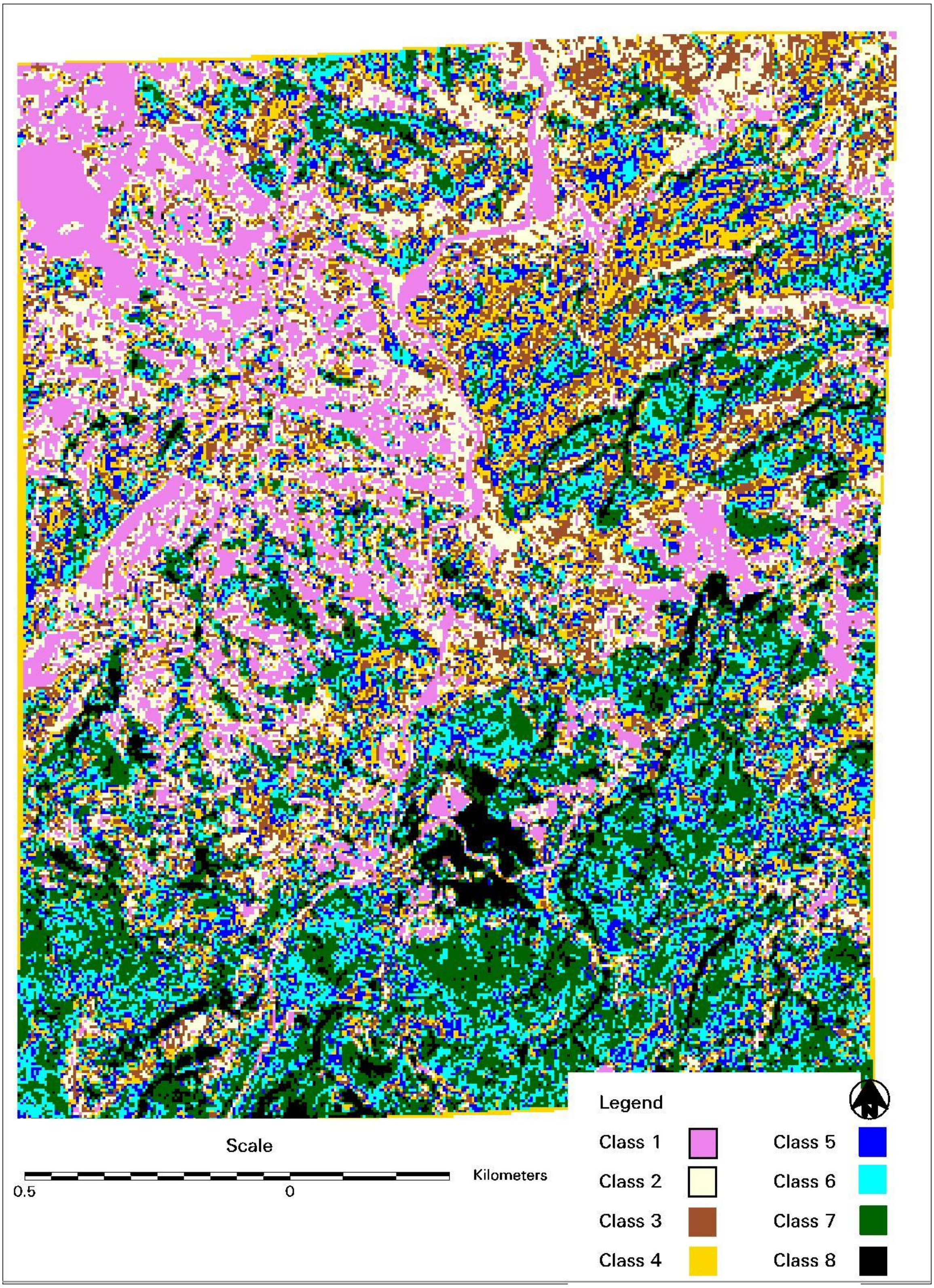


Figure 6.5 Eight class NDVI image

The 15x15m training area positions were overlaid onto the six class NDVI image. Training areas containing 50% or more of one NDVI class were allocated to that class. The training area cover data for the training areas in each NDVI class were averaged for each category of cover (Table 6.1). The results can be seen in Appendix 4. Table 6.2 shows the cover divided into live vegetation and other cover where other cover is defined as Bare Silt Crust, Stones and Litter. As can be seen from Table 6.2, class 2 to class 6 describes a gradient from very little vegetation to dense vegetation.[4] However, there is a slight anomaly as class 1 has more vegetation on average than class 2. This is explained in section 3.1.6.1.

Cover type / Class	Bare Silt Crust %	Stones %	Organic Crust %	Lichens %	Grasses %	Annuals %s	Shrubs >35cm %	Shrubs <35cm %	Litter %	Clump Grass >35cm %	Clump Grass <35cm %	# of TAs used
1	18.4	18.5	9.8	3.8	1.5	2.3	14.1	5.8	12.0	10.3	3.5	8
2	14.7	26.4	11.6	0.1	1.0	2.5	10.5	7.6	15.5	6.2	4.0	7
3	0.5	31.1	4.5	0.0	1.8	4.0	19.3	21.7	14.2	1.9	1.0	7
4	2.3	19.7	2.5	0.6	3.9	1.3	22.8	9.3	18.7	16.2	2.5	8
5	0.1	19.0	2.3	0.7	6.2	3.0	35.4	4.4	15.2	12.6	1.1	11
6	7.0	0.6	2.1	0.0	29.3	16.0	28.5	2.5	12.5	1.4	0.0	2

Table 6.1 Average landcover in training areas in each class of the six classes from the six class NDVI image

Class	Vegetated	Not vegetated
1	51.7	49.3
2	43.4	56.6
3	54.2	45.8
4	59.3	40.7
5	65.2	34.8
6	79.9	20.1

Table 6.2 Vegetated and non-vegetated cover by class

Figure 6.6 shows the locations of the training areas collected in 1997 and 1998 in the Mocatán and Infierno catchments. Below are detailed cover descriptions of each of the classes from the clustered image derived from the 1997 and 1998 training area data.

6.3.1 Class 1 cover

Cover values for class 1 show just over 50% of the cover is made up of either inorganic cover (stones or bare silt) or of the lowest plant forms (organic crust or lichen). Litter makes up another 12% of the cover. Higher plant species make up approximately 38% of the ground cover in this class, with shrubs over 35cm in height making up the largest proportion of this percentage. In the training areas surveyed that fall into this class, there was evidence of erosion (mostly rilling but sometimes pipe entrances/exits or gullies). Often, the flowering plants found in class 1 would be species such as

[4] It is likely that vegetation is over represented in classes one and two, as no field sampling was done in areas totally bare of vegetation.

Salsola genistoides, *Eryngium spp.* or *Limonium insigne*, all of which are salt-tolerant plants. *Salsola genistoides* is a plant which was found in 40 of the 65 training areas surveyed in 1997 and 1998, and was almost always one of the plants found in severely degraded sites where it was frequently found alone on the edges of gullies. Lazaro *et al* (2000) describe *Salsola genistoides* as a 'resistant' higher plant which can be found in areas of extreme erosion. The clump grass species found in class 1 sites were *Lygeum spartum* and *Stipa tenacissima*. Whilst *Lygeum spartum* was only found in training areas in classes 1,2 and 3, *Stipa tenacissima* was found in those of all classes. *Lygeum spartum* does appear to favour degraded sites where other vegetation is quite sparse. On average, nine plant species were recorded in class 1 training areas.

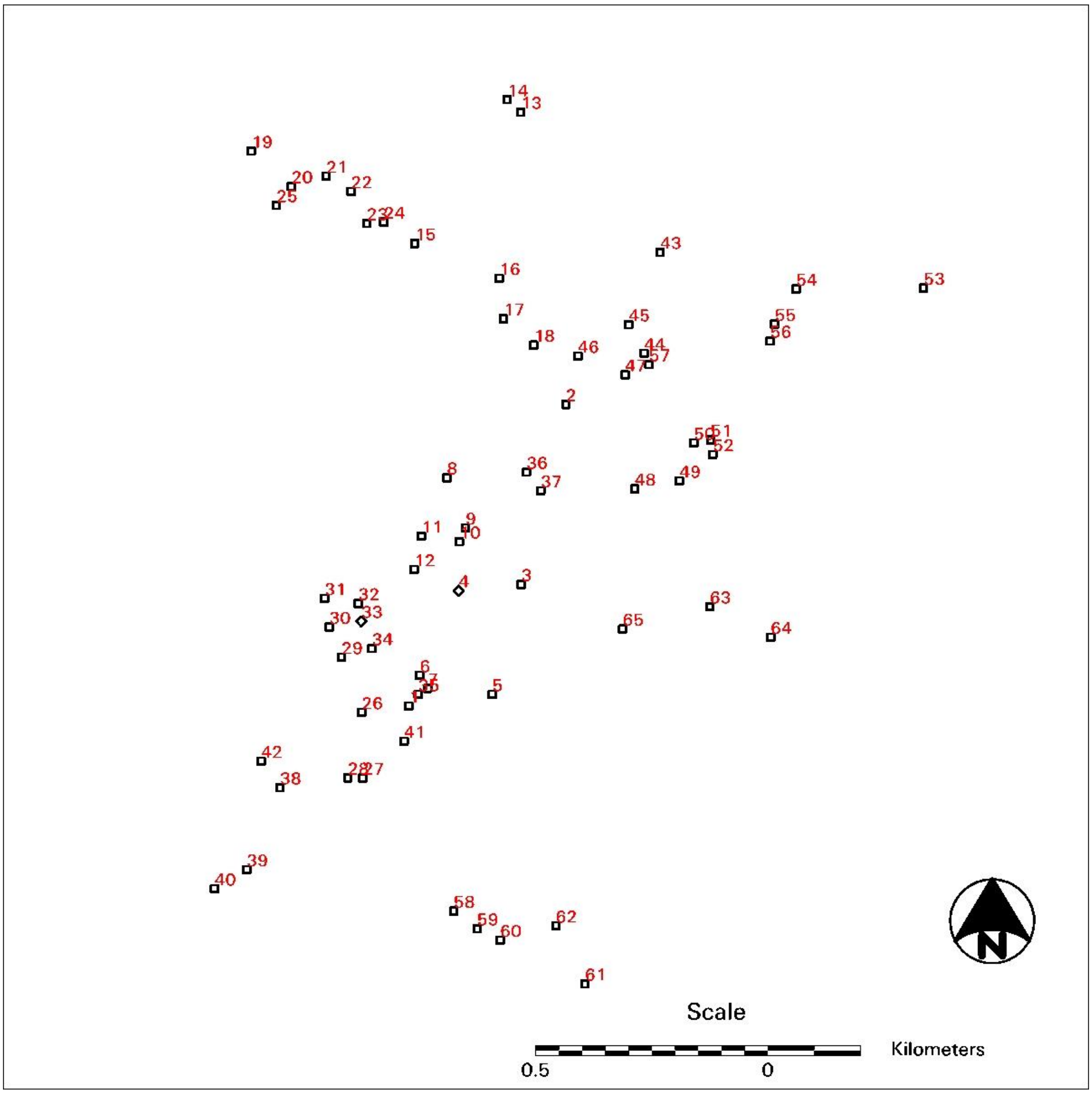


Figure 6.6 Location of the training areas collected in 1997 and 1998 (copy of figure 5.5)

An example of a class 1 training area can be found in plate 6.1. The photograph shows a SSE facing slope of about 25°. On this slope are a number of *Lygeum spartum* tussocks (the plants which are lighter green on colour) whilst the darker green plants on the gully edge are *Salsola genistoides*. There is also some standing litter (dead plants) visible in the foreground.

It is obvious from the photograph that this training area lies within an eroded area – gullying is present in the foreground and it can be seen that some of the plants are standing on 'pedestals' of stones and soil with slightly lower bare eroded areas all around them. Class 1 training areas are found exclusively on the Mocatán catchment side of the field area.

The anomaly that is exhibited by non-vegetated class 1 cover compared to non-vegetated class 2 cover can be explained to some extent by the sampling strategy in 1997. Areas that were completely bare of vegetation were not sampled as the aim was to sample vegetated areas. This means that the class 1 training area samples over-represent vegetation cover as no very bare training areas were sampled. Another factor in the difference in vegetated cover between class 1 and 2 is likely to be the difference in colour between MRU and TRU geology with the lighter, very reflective TRU drowning out the signature of the sparse vegetation cover found in class 1 areas.

Although class 1 has more vegetation cover than class 2, the class separation appears to have taken place on low plant cover and brightness of underlying sediment. Class 1 training areas demonstrate that the NDVI clustering has successfully separated this class out from the rest of the cover on the basis of sediment colour, and to a lesser extent, bare silt crust cover.

6.3.2 Class 2

Average class 2 cover varies slightly from that of class 1 in that it has a much higher proportion of stones. At 53% bare ground and lower plant cover, class 2 has, on average, less vegetation cover than class 1. Litter makes up a further 15% of ground cover. Large shrubs are the higher plant form with the largest presence in class 2, making up just over 10% of the total. Total higher plant cover in class 2 training areas is approximately 32% of total cover which is actually lower than class. Unlike class 1, class 2 training areas are found both in the Mocatán catchment and in the Infierno catchment, where the MRU sediment is darker than the TRU sediment in the Mocatán catchment.

Class 2 training areas do not appear to exhibit quite as much erosion as those of class 1. Stone cover frequency is greater in class 2 than class 1 and the stone armouring appears to inhibit the formation of rills in contrast to the situation in areas of bare silt crust. However as can be seen in the class 2 training area shown in plate 6.2, there is a rill/small gully visible in the foreground. In plate 6.2 there is stony cover interspersed with plants which mainly consist of small and medium sized clumps of *Launea spinosa, Salsola genistoides* and tussocks of *Stipa tenacissima* (there is a good example of a *Stipa* tussock in the bottom right hand corner of the photograph). As well as the larger shrubs and grasses, there is also a scattering of small shrubs, including *Thymus spp*, *Eryngium spp* and *Artemisia spp*. On average, class 2 training areas contained 11 plant species.

Class 2 has been separated from the rest of the NDVI image by sediment colour and to a lesser extent by coverage of stones.

Plate 6.1 Training area 9 showing cover in class 1

Plate 6.2 Training area 2 showing cover in class 2

6.3.3 Class 3

In class 3, average bare silt crust cover drops to less than 1% as compared to 14% or more in classes one and two. Stone cover rises to 31% which is the highest average stone cover for any of the classes. Average organic crust and lichen cover is very low. In total the cover of bare ground and lower plants is 36%. Litter makes this total up to 50%, so for the first time, live higher plant cover has reached half of the total ground cover. Small shrubs make up approximately 22% of the cover in class 3. Commonly found shrubs under 35cm in height included woody perennial species such as *Thymus spp*, *Euphorbia spp.*, *Phagnalon rupestre* and *Sedum sediforme*. Larger shrubs (over 35cm in height) included *Anthyllis spp.*, *Salsola genistoides* and *Thymelea hirsuta* in both catchments, and *Ulex parviflorus* and *Cistus spp.* in the Infierno catchment training areas. Soft grasses contributed little to the cover of class 3 training areas. Annuals were more common in class 3 than any other class except class 6. Annuals found in class 3 sites included *Siderites spp.*, *Diplotaxis crassifolia* and *Pallenis spinosa* but were more often unidentifiable species which were put into family groups, for example compositae, leguminosae or cruciferae. Clump grasses, large and small comprised less than 3% of average cover in class 3 training areas.

Plate 6.3 shows an example of a class 3 training area in the Infierno catchment. It can be seen that plant cover is much denser here than in classes one and two, but it is still possible to see stones through the vegetation. In the foreground of the photo can be seen a large number of *Ulex parviflora* bushes, and between these can be seen much smaller plants, some of which have yellow flowers (on the centre left). This is likely to be *Helichrysum italicum* which rarely grows above 35cm in height and is therefore classed as a small shrub. The small shrub layer can be seen to be covering the ground between the larger shrubs, and it is easy to see how this can make up almost 22% of total cover on average. The oblique angle of the photograph appears to suggest more than 50% cover by live vegetation, but when viewed from above, the bare ground between the plants becomes more visible. This effect can be seen in the foreground where the cover appears more sparse.

The six class NDVI clustering appears to have successfully separated areas with approximately 50% plant cover from areas which have less ground cover. Class 3 consistently describes areas with a covering of about 20% small shrubs. No other training areas have this high an amount of small shrub cover or such a low amount of clump grasses. Class 3 is clearly different from classes 1 and 2, and also classes 4, 5 and 6.

Plate 6.3 Training area 43 showing cover in class 3

6.3.4 Class 4

Bare ground and lower plant cover drops to 25% of the total in class 4. The largest proportion of this is accounted for by stones at approximately 18%. Litter makes up another 18.7% which is the highest percentage achieved by this cover type in any of the classes. This leaves 56% live higher plant cover in this class. One of the major distinguishing features of class 4 is the high proportion of clump grass; up to almost 19%, and the highest amount of this type of cover for any of the classes. Large shrubs make up approximately 23% of the total cover, but small shrubs are down to 9%.

Class 4 is a less coherent class than class 3 as it appears to describe two very different cover types; one found mainly in the Infierno catchment and the other found mainly in the Mocatán catchment. In the Mocatán catchment class 4 generally (but not always) describes cover with a high proportion of large shrubs, but also a very high proportion of litter. In the Mocatán catchment there is not as much clump grass in class 4 training areas as in those of the Infierno catchment. The Infierno training areas have an average of 27.6% clump grass cover and 22.5% stones. The training areas in this class also appear as being different areas in the two catchments as plates 6.4 and 6.5 show. It appears that the clustering process resulted in areas with high amounts of litter and large shrubs being class 4, along with areas of high clump grass cover associated with a stony ground cover. These two types of cover, whilst appearing dissimilar on the ground, clearly have similar spectral signatures in the bands used for NDVI and so were placed in the same class. The two cover types are not found exclusively in one or other of the catchments. The stones and clump grass (always *Stipa tenacissima*) component of this class is always found on the tops and sides of ridges, for instance on the top of Cerro de Juan Contreras and on the ridges running down into the Infierno catchment from the gypsum track. The litter and large shrubs component of this class can be found on abandoned terraces in both catchments which appear to have been degraded by piping where once dense, shrubby vegetation has died and is now standing litter.

The plant species that were found in the ridge top cover included large numbers of *Stipa tenacissima* tussocks, *Ulex parviflora*, *Anthyllis spp. Cistus spp.* in the Infierno catchment and *Fumana ericoides*, a small *Helianthumum*-type perennial shrub. Along with these were the usual small shrubs including *Phagnalon rupestre*, *Thymus spp* and *Artemisia spp.* Annuals and soft grasses were not much in evidence in these training areas. The plant species found in the degraded terrace type of class 4 cover included *Anthyllis spp*, *Salsola spp*., *Thymelea hirsuta*, *Launea spinosa* and *Dorycnium pentaphyllum*. Interestingly, *Dorycnium pentaphyllum* is more normally associated with class 5 training areas which would perhaps indicate that the class 4 areas of dense standing litter are degraded class 5 type cover. The average number of plant species found in a ridge top, stony class 4 training area was 12, and the average number found in the dense litter and large shrubs class 4 cover was nine.

Plate 6.4 Training area 29 showing class 4 cover in the Mocatán catchment

Plate 6.5 Training area 57 showing class 4 cover in the Infierno catchment

6.3.5 Class 5

Bare ground and lower plant cover averaged 22% in class 5 training areas, with litter 15% on average. Class 5 is characterised by a high average cover of large shrubs which at 34% of the total cover is higher than any other cover type in any of the other classes. Average cover of clump grass is relatively high too at 12.6%. Total cover of higher plants is approximately 63%. The highest bare ground cover is that of stones which make up 19% of the total cover. Class 5 has barely any understorey of small shrubs, annuals and soft grasses, it is mainly characterised by the large shrubs and clump grasses with stones in between. There were few species found in class 5 training areas that were not recorded in other less dense training areas. However, some species occurred in larger amounts or as bigger plants in class 5 training areas, for example *Dorycnium pentaphyllum* which was found in training areas of all classes mostly appeared as a large shrub in class 5, whereas it was normally a small shrub in classes 1 to 4. Clump grasses recorded in class 5 were always *Stipa tenacissima*. *Lygeum spartum* was not found in any class 5 training areas..

Plate 6.6 shows an example of a class 5 training area in the Infierno catchment. It can be seen that the cover of shrubs is dense with a little bare stony ground showing through. In the foreground are *Cistus spp*. plants interspersed with some *Anthyllis spp*. bushes. There was no evidence of rilling or gullying at this training area, the stone armouring of the soil appearing to inhibit the formation of rills.
Class 5 appears to be a robust class as it describes similar cover in both the Infierno and Mocatán catchments. The composition of the live plants varies slightly between a dense cover solely composed of large shrubs and one comprising a mixture of large clump grasses and large shrubs. The class represents similar amounts of dense, large vegetation in all cases.

6.3.6 Class 6.

Only two training areas from the 1997 and 1998 field seasons fell into class 6 areas of the NDVI image and hence the interpretation of this class is based on a very small sample. However, the cover amounts from both training areas are reasonably similar, and are significantly different from classes one to five. Class 6 has less than 10% bare ground (i.e. bare plus lower plant life cover) and a large shrub cover of approximately 29%, litter cover of 12.5% and very little clump grass (1.4%). What makes class 6 very different to the other five classes is the high percentage cover of both soft grasses and annuals at 29% and 16% respectively. These cover types effectively form an understorey which leads to the difference between class 6 and class 5 in the six class NDVI image. Plate 6.7 shows a class 6 training area.

It can be seen in plate 6.7 that the training area is very well covered by vegetation and there is little bare ground showing through.

Plate 6.6 Training area 65 showing class 5 cover

Plate 6.7 Training area 51 showing class 6 cover

The NDVI clustering has identified this distinctive class which has very high amounts of green vegetation cover. The difference between this class and class 5 is the very high levels of annuals and soft grasses, the average number of plant species identified was 23. Although the sample size for class 6 is very small, both training areas demonstrated a difference from the other training areas sampled.

6.4 TWINSPAN cover analysis and NDVI class

One of the major reasons for carrying out TWINSPAN analysis (Section 3.4 and 3.6) was to use the end groups to aid the interpretation of the clustered NDVI images, and indeed the cover types measured in the field were derived with this in mind. It was hypothesised that the cover TWINgroups would show a relationship to the six NDVI classes. Each training area was assigned an NDVI class depending on the dominant pixel values contained within the training area boundary when it was overlaid on the six class NDVI image. As can be seen in Table 6.3 there was not a close relationship between many of the TWINSPAN groups and the six class NDVI image. However, TWINSPAN picks out the structure of the cover and not necessarily the density of green vegetation. Comparing vegetation cover density with TWINSPAN group it can be seen that the total green plant cover (that is all the 'live plant' categories added up) varies widely (Table 6.4)

	NDVI class						
Cover group	**1**	**2**	**3**	**4**	**5**	**6**	**Total**
A	2						2
B	2		1	4	3		10
C			1	3	4		8
D		3	7	1	3		14
E	1	1	1	1			4
F	2	3	1		1		7
G		1		1			2
H		2	2		2		6
I	1	2	1		1		5
J	1		1	1	2	2	7
Total	9	12	15	11	16	2	65

Table 6.3 Crosstabulation of cover TWINSPAN group and NDVI class

Taking TWINgroup 4 as an example, it can be seen that live plant cover in the training areas varies widely between 20% and 73%. TWINgroup 4 has training areas in four of the six NDVI classes. NDVI class is significantly correlated with total amount of live vegetation ($P<0.05$, two-tailed Pearson test), which would explain why the TWINSPAN groups do not fall neatly into NDVI classes.

Twingroup	TA #	Total vegetation	Twingroup	TA #	Total vegetation
1	9	19	5	15	49
1	32	33	5	23	78
2	13	53	5	28	38
2	22	49	5	29	70
2	31	60	6	8	61
2	37	55	6	11	22
2	39	56	6	20	39
2	40	65	6	21	40
2	44	71	6	24	39
2	57	65	6	33	28
2	61	65	6	64	45
2	62	51	7	10	52
3	12	71	7	30	43
3	18	55	8	1	68
3	34	70	8	6	20
3	41	59	8	14	46
3	43	66	8	26	37
3	46	82	8	35	58
3	53	55	8	42	68
3	60	74	9	4	55
4	2	20	9	19	65
4	3	37	9	25	71
4	5	48	9	38	70
4	7	73	9	55	59
4	17	39	10	16	79
4	27	28	10	36	77
4	45	49	10	47	65
4	48	39	10	51	76
4	49	63	10	52	64
4	50	38	10	56	79
4	54	57	10	63	59
4	58	54			
4	59	50			
4	65	62			

Table 6.4 TWINgroup and total plant cover on each training area

6.5 Verification of six class NDVI image with the 2000 data

The purpose of fieldwork in 2000 was to verify the six class NDVI image and its interpretation based upon the 1997 and 1998 data. Instead of using 15x15m training areas, 3x3m quadrats were used. This was mainly due to time constraints. There was less than a week to carry out fieldwork and at least 8 quadrats in each of classes three to six were needed. Classes one and two were not concentrated on in the 2000 fieldwork as they were sparsely vegetated and it appeared that the underlying sediment was controlling the spectral response and thus the NDVI image and clustering. However, two quadrats were collected in areas of class 2 cover. The use of 3x3m quadrats allowed more detailed sampling of smaller areas of cover than was possible using 15x15m training areas.

A paper copy of the clustered NDVI image was taken into the field to aid identification of patches of classes 3 to 6 for surveying. Using this map, an *ad hoc* stratified sampling method was used to identify areas where samples could be taken in the field. As the sampling level aimed for was eight quadrats in each class, it was attempted to carry out four quadrats in each class in both catchments. Quadrats were chosen by class and by position in the catchments whilst in the field. At each of these quadrats a GPS reading was taken, but due to a fault in the equipment, all GPS readings were lost. However, a knowledge of the field area and use of the clustered NDVI image, ensured that each quadrat was placed entirely within a single NDVI class and the position of each could be located on the image to within ± 5m. Hence all quadrats were placed in areas that represented several contiguous pixels of a single class on the image. These quadrats and their positions in the field area can be seen in Figure 6.7.

Instead of taking a measurement at every metre, percentage cover of each cover type (the same cover types as in 1997 and 1998) was estimated by eye, and cover of individual species were noted down using the Braun-Blanquet scale. Average cover for classes 2 to 6 is given in Table 6.5.

Cover type / Class	Bare Silt Crust %	Stones %	Organic Crust %	Lichens %	Grasses %	Annuals %s	Shrubs >35cm %	Shrubs <35cm %	Litter %	Clump Grass >35cm %	Clump Grass <35cm %	# of quadrats
2	15.0	42.5	25.0	1.0	0.5	1.5	6.0	4.5	6.5	0.0	3.5	3
3	20.5	21.9	8.3	1.9	4.1	5.5	6.6	16.5	10.0	3.9	1.5	10
4	7.3	25.4	10.8	2.1	2.6	3.7	7.6	4.7	9.6	25.8	0.6	10
5	2.9	14.0	5.7	1.5	1.7	6.0	41.1	10.7	11.6	4.0	1.0	11
6	2.4	1.5	1.6	0.5	15.3	20.9	29.8	8.8	13.5	5.5	0.8	11

Table 6.5 Average cover type by class for quadrats surveyed in 2000 field season

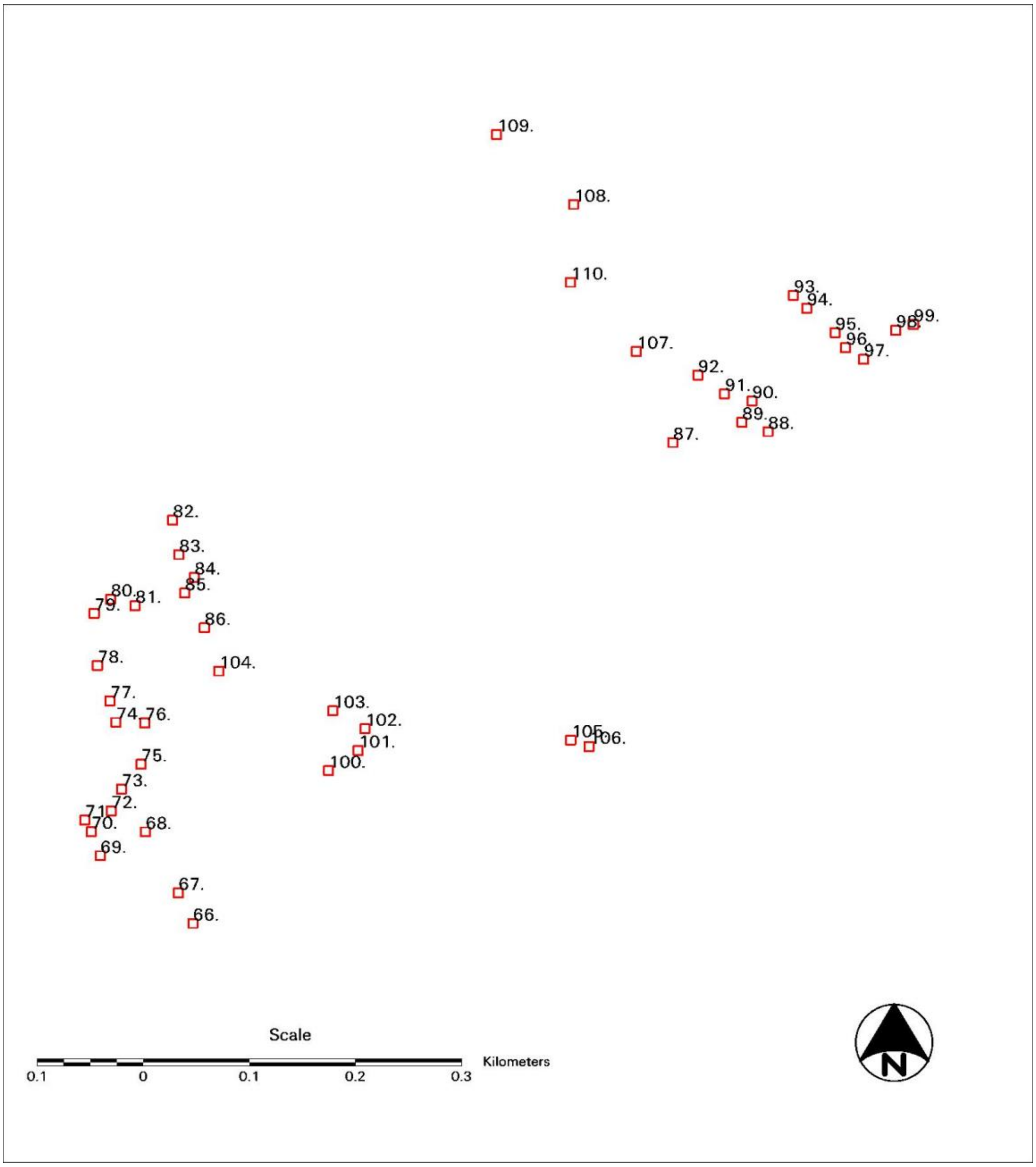


Figure 6.7 Positions of fieldwork 2000 3x3m quadrats

Table 6.6 is the equivalent of Table 6.2, displaying the total vegetation and non-vegetation cover for the 2000 cover values. The final two columns in the table demonstrate the difference between the cover values for each class in 1997/98 and 2000. The differences between the 1997 and 1998 training area cover values and the 2000 quadrats are given in Table 6.7. Training areas are defined as being the 15x15m areas used to collect cover data in 1997 and 1998, quadrats are defined as the 3x3m areas used to collect cover data in 2000.

Class	Vegetated	Non vegetated	Difference between vegetated	Difference between non vegetated
2	36.5	63.5	-6.9	6.9
3	47.6	52.4	-6.6	6.6
4	57.8	42.3	-1.5	1.6
5	71.5	28.5	6.3	-6.3
6	82.6	17.4	2.7	-2.7

Table 6.6 Vegetated and non-vegetated cover by class for 2000 quadrats with the difference between 1997/98 and 2000 quadrats

The figures in Table 6.7 are calculated by subtracting the 1997/1998 average class cover values from the 2000 average cover class values; a positive value means that that there is more of that particular cover type in the 2000 quadrats, and a negative value indicates less of that cover type in the 2000 quadrats. Most of the 2000 values agree to within ±5% of the 1997/1998 values, but there are a few cases where values are greater than ±10%.

Cover type Class	Bare Silt Crust %	Stones %	Organic Crust %	Lichens %	Grasses %	Annuals %s	Shrubs >35cm %	Shrubs <35cm %	Litter %	Clump Grass >35cm %	Clump Grass <35cm %
2	8.6	10.1	9.3	0.8	-3.4	-3.1	-8.0	-1.3	-7.0	-2.5	0.0
3	10.3	0.7	2.2	1.0	-0.5	0.2	-12.2	2.6	-2.9	-1.3	0.5
4	1.3	5.1	4.3	1.1	-1.8	0.4	-7.2	-1.8	-5.1	5.1	-0.7
5	1.8	-2.7	0.4	0.4	-1.4	3.9	-2.0	1.1	-2.1	1.0	-0.3
6	-1.2	1.0	0.6	0.4	1.6	-0.3	-1.0	4.1	-1.4	-4.1	0.6

Table 6.7 Differences between 1997/98 cover values and 2000 cover values (absolute values)

It appears that there is an increase in the amount of bare ground throughout the year 2000 quadrats in classes 2, 3 and 4, with the largest changes being in classes 2 and 3. These two classes show corresponding reductions in the cover of vegetation composed of higher plants. The reductions are particularly noticeable in large shrub cover, where class 2 has 8% less cover in 2000, and class 3 has 12.2% less. This reduction in higher plant cover could be explained by lower rainfall in 1999 and 2000 than in 1997 and 1998. Precipitation amount in 2000 (as measured at Almería airport) was low prior to fieldwork commencing with approximately 100mm falling from October 1999 to April 2000, and, of that, only 27mm falling between January and April (www.weatheronline.co.uk, 2001). This is compared to precipitation totals between October 1997 and April 1998 of approximately 215mm (93mm of which fell between January and April); and between October 1996 and April 1997, a total of 147mm of which 60mm fell between January and the commencement of fieldwork in April. Thus rainfall totals were higher in the months preceding the 1997 and 1998 fieldwork than those months preceding the 2000 fieldwork, possibly leading to changes in leaf area and green vegetation quantities.

Sampling done in 1997/1998 was carried out prior to clustering of the ATM image, and most of the training areas surveyed were found to contain mixed classes of pixels when the training areas and the clustered NDVI were later overlaid. This would imply that the data from the training areas are less than perfect for defining the classes in the classification. The 2000 quadrats were, however, sited within known areas of the individual classes and so are likely to be more representative of those classes (this being the main reason for the post-clustering fieldwork being done after investigation of the image which allowed quadrats to be placed accurately within classes). Taking the 2000 quadrats as being more representative of the six class NDVI image would mean that the figures for cover in Figure 6.3 should be regarded as the definitive cover totals for the 5 classes (classes 2 to 6) surveyed. Class 2 quadrats were very sparsely vegetated with a high level of stone cover, as can be seen in Plate 6.8 which shows an example of a class 2 quadrat.

10% more bare silt crust was recorded in class 3 quadrats in 2000 than in 1997 and1998, with a corresponding fall in the amount of large shrubs recorded. This indicates that NDVI class 3 contains a cover of mixed bare silt crust and stones, vegetated with small shrubby plants. The description of this class made using the original training areas appears to give a similar cover profile, except for the higher quantities of bare ground, and in both cases, class 3 has the second highest cover of annual plants. Plate 6.9 shows a class 3 quadrat.

Plate 6.8 An example of class 2 cover as seen in quadrat 110

Plate 6.9 Quadrat 94 showing class 3 cover

Class 4, which appeared to be a split cover class when the training area data from 1997 and 1998 were investigated, has all but one of the eight quadrats collected in 2000 fall into the clump grass and stones category. This explains the drop in large and small shrub cover between the 1997 and 1998, and 2000 surveys, and the comparable increase in large clump grasses in 2000. As class 4 quadrats were collected in both catchments and in valley bottoms as well as ridge tops, it would appear that the clump grass and stones type class 4 cover is more common than the litter and large shrubs type. Average clump grass cover is higher and large shrub cover is lower in 2000 than in 1997 and 1998 as would be expected if more clump grass and stones cover was observed. Class 4 in 2000 appears very similar to the clump grass and stones type of class 4 as described after the 1997/1998 fieldwork. However, the presence of one quadrat of shrubs and litter type cover out of the eight quadrats collected in class 4 indicates that the clustering still holds for both types of cover. An example of stones and clump grass class 4 cover can be seen in plate 6.10.

Class 5 shows the greatest similarity between the average cover values for 2000 and those for 1997 and 1998. The most significant difference between the two sets of figures is that there is a 3.9% rise in the percentage of annuals recorded in class 5 quadrats in 2000. It appears that class 5 is a robust group which was easily identifiable in 1997 and 1998 and in 2000. An example of class 5 cover is given in Plate 6.11.

There is also little change between class 6 as surveyed in 1997/1998 and 2000. The biggest difference found was that average cover values for annuals and large shrubs were slightly lower in 2000 whilst small shrub cover was slightly higher. An example of class 6 cover is given in Plate 6.12.

Comparison of the field data for 1997/1998 and 2000, indicate similarities between NDVI class groupings of cover data. The two sets of data seem to be similar and the clustered six class NDVI image should be accepted as it stands with a proviso that classes 2 and 3 may have higher proportions of bare ground cover types than originally surveyed in 1997 and 1998. The difference in cover in these two classes may be explained by the low rainfall totals as discussed earlier in this section. The difference could also be explained as a change in choice of area to sample 1997 and 1998 sampling always took place in cover with at least some vegetation and very bare areas were avoided. However, when using the NDVI image, areas of individual classes were sampled regardless of the cover amount. Thus the sparser end of class 2 was sampled in 2000 where previously it would not have been sampled. However, it is acknowledged that classes 2 and 3 may have some overlap when comparing results of training areas and quadrats. The rest of the classes describe different landcover types which have little overlap and so can be used in further analysis and classes 2 and 3 will continue to be used as originally defined. The descriptions of the classes which appear earlier in this chapter will remain valid throughout the rest of the analysis to be presented later on in this thesis which includes analysis of environmental variables (aspect, slope and wetness values) in the latter half of this chapter, and a landscape ecological quantification of landscape pattern in Chapter 7.

Plate 6.10 Class 4 as seen in quadrat 93

Plate 6.11 Class 5 cover as seen in quadrat 83

Plate 6.12 Class 6 cover as seen in quadrat 95

6.6 Analysis of environmental variables using the clustered image

Having established a consistent interpretation of the NDVI classes using the ground data, the NDVI image could be used as a cover map for the whole study area and analysed together with other datasets (slope, aspect and wetness) in order to investigate land cover patterns and their relationships with environmental factors.

The study area does not contain homogenous landcover. Some areas of the study area have different cover patterns to other areas, and these differences are quite distinct. Rather than examining the study area as a single unit, the clustered image was divided into two along the watershed between the Infierno and Mocatán catchments (Figure 6.8). The image was then further subdivided in order to examine characteristic landcover patterns in areas of smaller extent. Four such areas were identified and were named Mocatán, Malaguica, Juan Contreras badlands and Sorbas (Figure 6.9). These four areas were all chosen as they have had less agricultural disturbance than the study area as a whole. The Mocatán badlands area was subset as it contains the most extensive areas of badlands in the study area, and the most characteristic cover of this type of terrain. The Malaguica area was subset as it contains a very distinct pattern of cover with well vegetated valleys and more sparsely vegetated hillsides. The Juan Contreras badlands were subset from the larger image as this area has a distinctive landcover pattern compared to the rest of the Infierno catchment centred upon a large area of bare badlands. The Sorbas area was subset as its cover is characteristic of the Sorbas member hills in the south of the study area with less patchy cover and fewer areas free of vegetation. Figures 6.10 and 6.11 show these same areas as they appear in the clustered NDVI image. The subsetting of the clustered NDVI image was carried out using the 'subset image' routine in ERDAS Imagine where the areas of interest were delineated using a vector tool to create a polygon. This polygon was then 'cut out' of the main image to give a clustered NDVI image of the area of interest. When a smaller area is subset from a larger one, the software creates a new attribute table for the raster grid. Analysis was carried out on these smaller areas using the variables aspect, slope and wetness index.

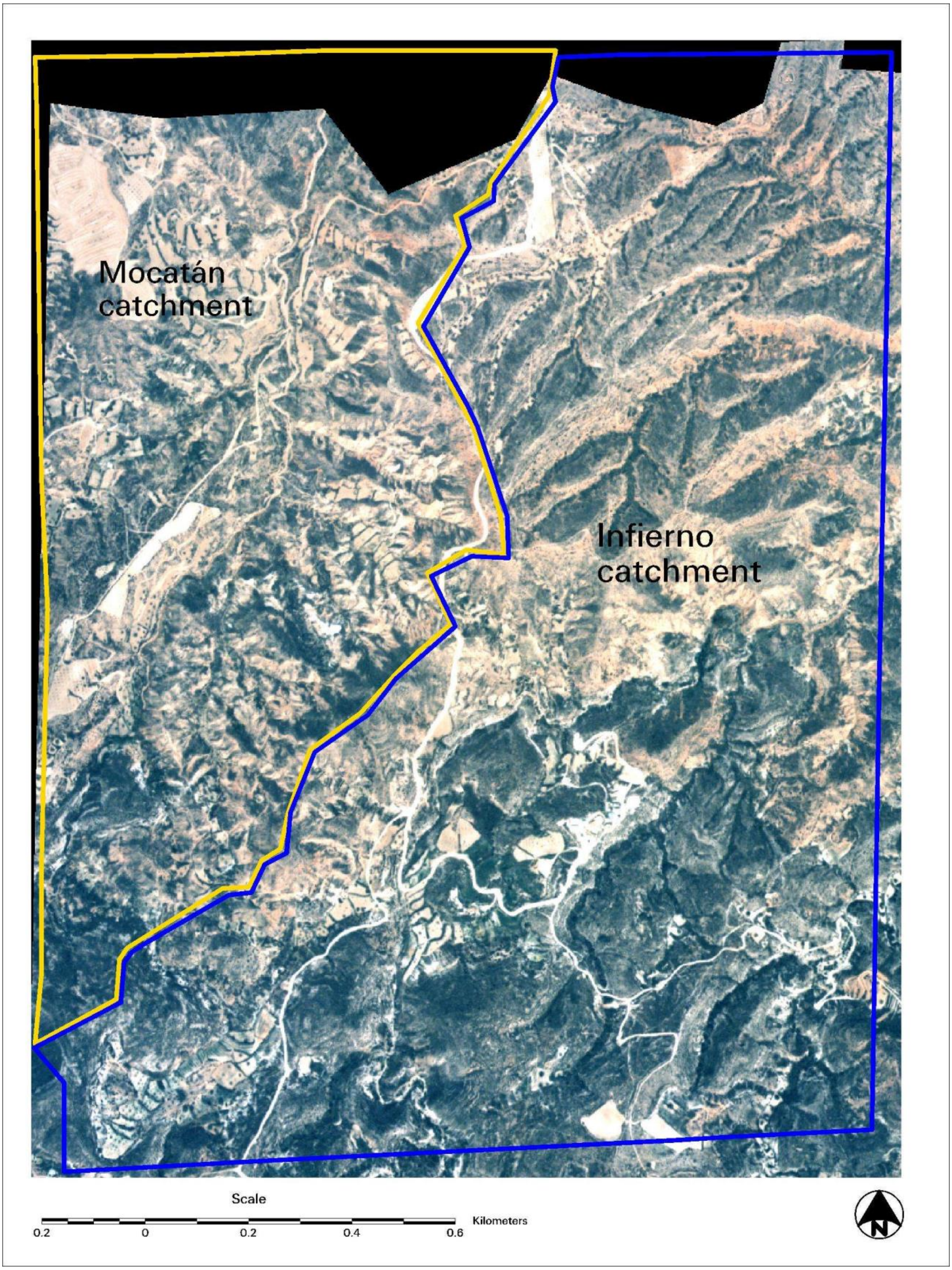


Figure 6.8 Mocatán and Infierno subsets used in analysis of cover data

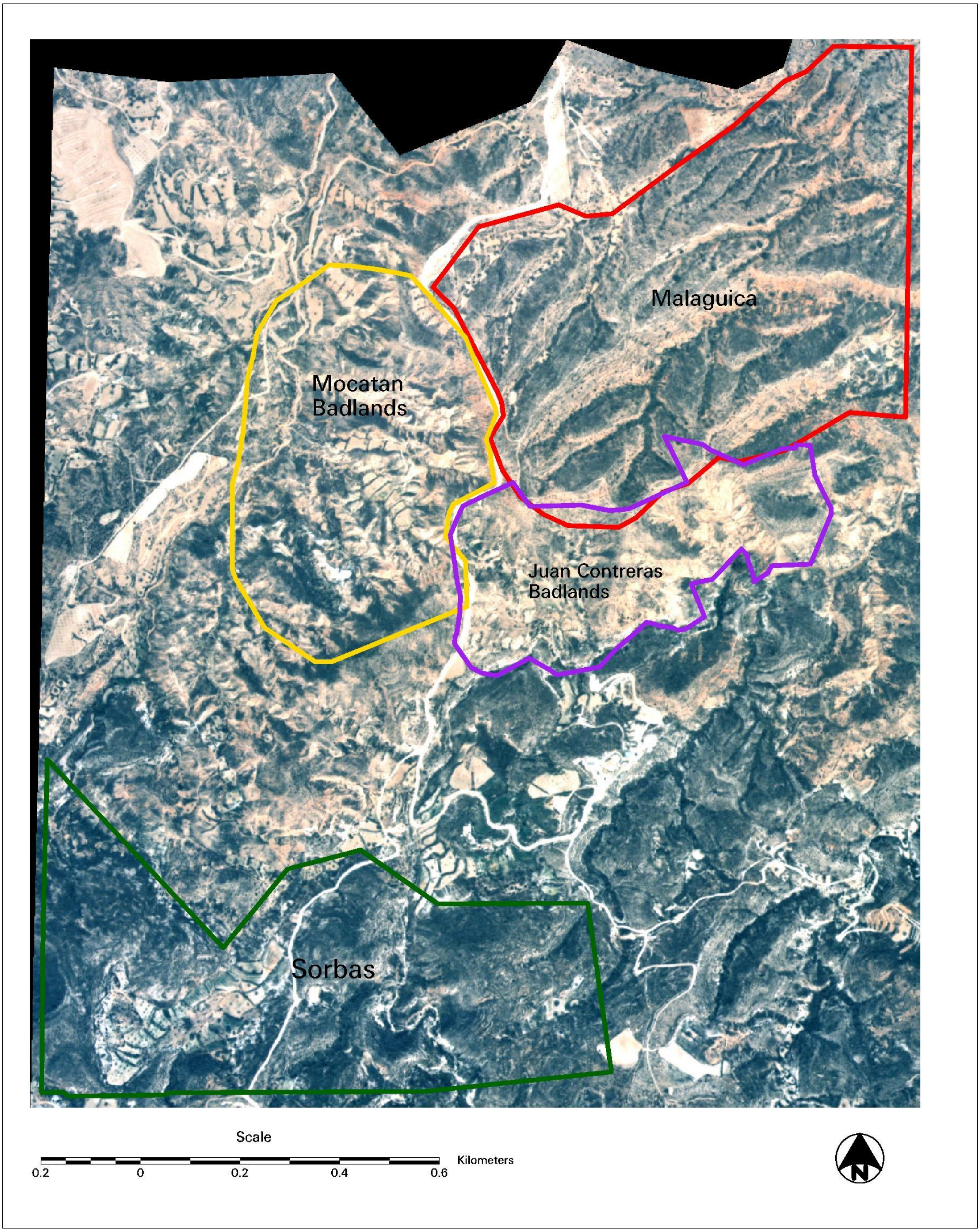


Figure 6.9 Areas of similar cover charateristics used in analysis of cover data

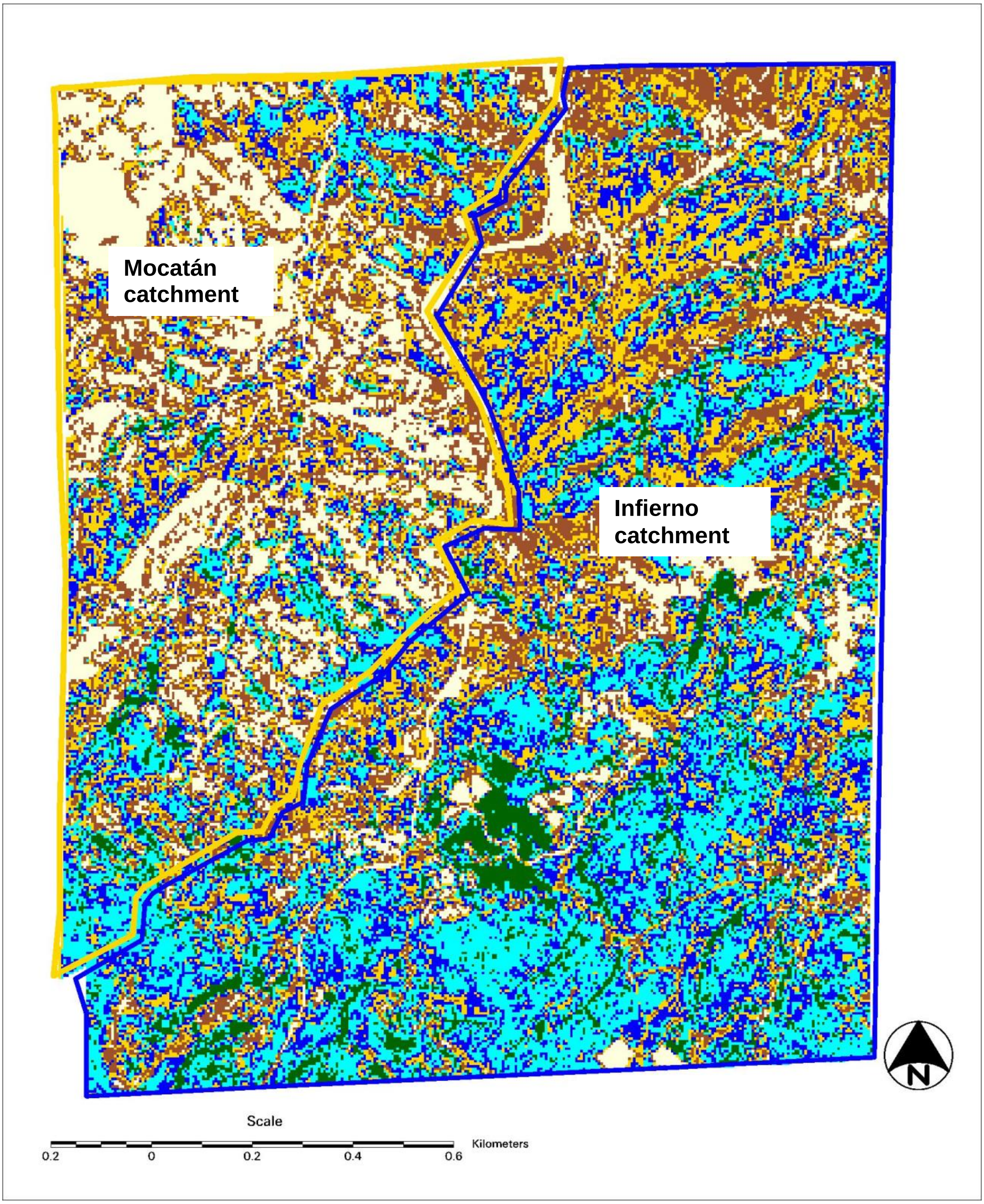


Figure 6.10 Catchment NDVI subsets

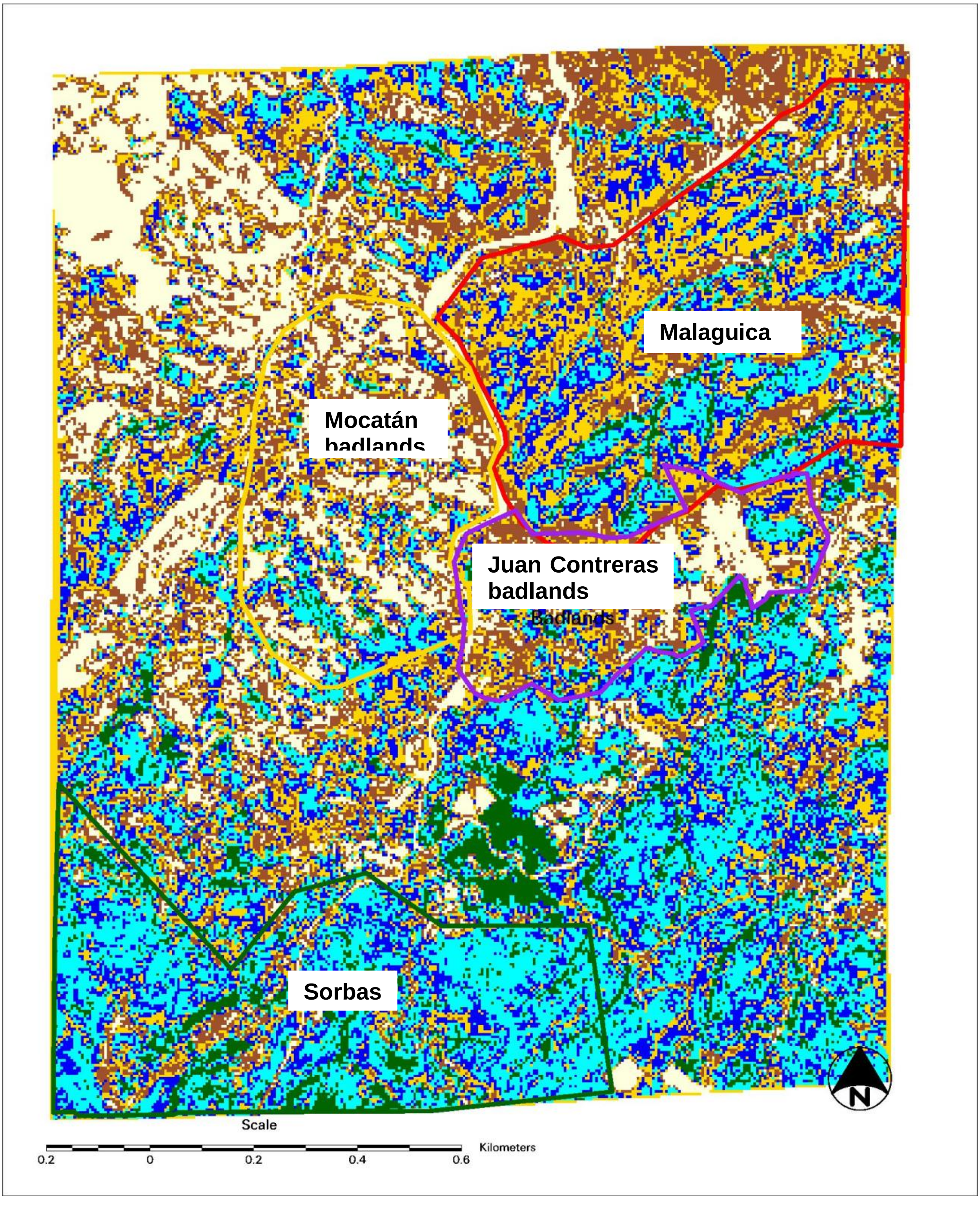


Figure 6.11 Sub-catchment clustered NDVI subsets

6.6.1 Clustered NDVI image and aspect

The aim of investigating the aspect data within the study area is to ascertain relationships between landcover as described by the clustered NDVI image, and aspect. As discussed in Chapter 2, it has been demonstrated elsewhere that slopes with different aspects have different amounts of vegetation cover due to variations in moisture stress throughout the day. If this holds true in the study area, (and Kirkby *et al* (1990) comment that the greatest aspect contrasts are to be found in the semi-arid mid-latitude regions where cloud cover is low) then vegetation cover on south and south-west facing slopes should be less than that on north and north-east facing slopes. Aspect statistics (from 1 to 360º) are available for each pixel of the aspect image of the study area. With ERDAS Imagine it is possible to use the 'mask' routine to extract aspect data for each of the six classes of the clustered NDVI image. The area of the class of interest from the clustered NDVI image is used to collect data from the aspect image so that only data in the area of interest (i.e. the area which that class covers) are collected. This means that pixel statistics solely for class x can be viewed enabling analysis of aspect by class to be carried out.

There is a discrepancy between pixel sizes in the aspect image (and all other products of the DEM) and those in the clustered NDVI image, in that the aspect image has a pixel size of 2m whereas the clustered NDVI image has a pixel size of 5m. The masked aspect images have a 2m. The rule that Imagine applies in this situation is that it includes pixels which are partially masked by the masking image in the output image (ERDAS, 1999). Therefore some pixels were counted twice as a 5m pixel placed directly over a raster of 2m pixels masked out four whole pixels, four half pixels and one quarter pixel (Figure 6.12). This pixel size discrepancy meant that the masked area of the aspect was slightly greater than the actual area of the class that was used as a mask. However, the discrepancy was less than 1% when total class area at 5m resolution was compared to total masked class area at 2m resolution.

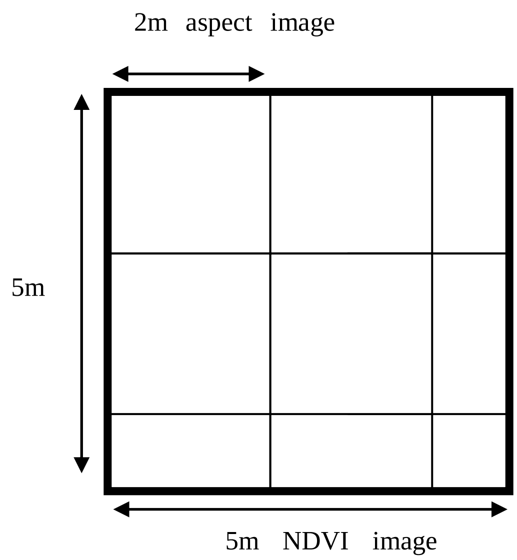
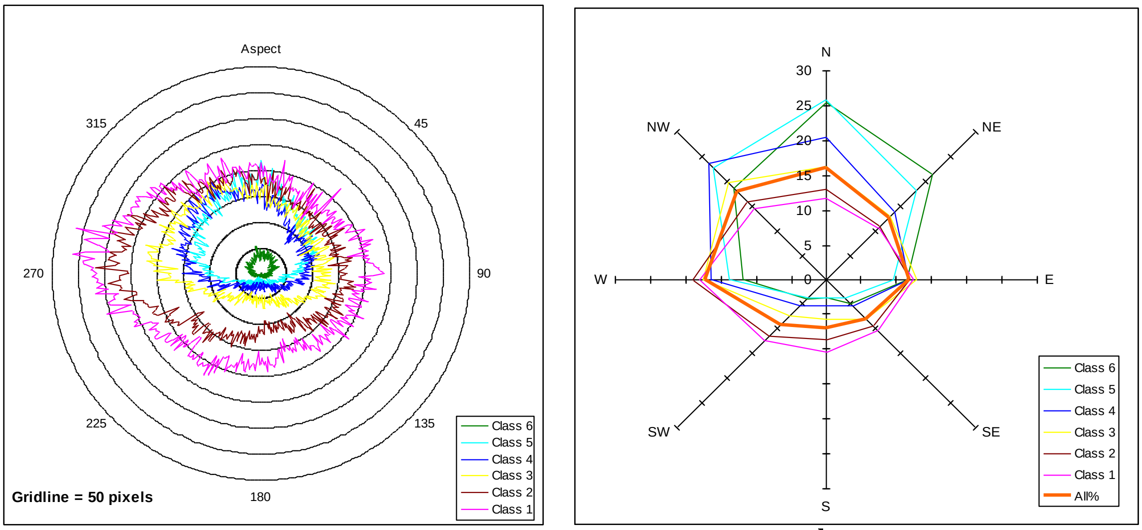


Figure 6.12 Mismatch of pixel sizes between DEM derived images and ATM data derived images

6.6.1.1 NDVI and aspect in the Mocatán catchment

The aspect image for each of the classes has each pixel assigned to one of the 360 degrees of the compass circle. Pixel numbers for each aspect in the Mocatán catchment have been plotted as a rose diagram in Figure 6.13(a). This amount of data is unwieldy to work with, so pixels degree values were subset into eight compass directions, north (339º-360º and 1º-23º), north east (24º-68º), east (69º-114º), south east (115º-158º), south (159º-203º), south west (204º-248º) west (249º-293º) and north west (294º-338º) and then plotted as percentages of each class (Figure 6.13b). Figure 6.13(a) shows a rose diagram showing the aspect for the Mocatán catchment where it can be seen that classes 1 and 2 make up the majority of landcover in the Mocatán catchment. The rose diagram shows that many of the class 1 and 2 pixels to face south-west and west. The pixels of classes 3, 4 and 5 which cover less of the land in the Mocatán catchment show a marked difference to the pixels of classes 1 and 2 as they have north westerly and northerly orientations. Class 6 is different again, having pixels with predominantly northerly and north easterly orientations.

Figure 6.13(b) illustrates the aspect pattern shown by pixels in the Mocatán catchment as percentage of each of the eight aspect categories. The rose diagram demonstrates that class 6, as would be expected from the densest vegetation cover occurs predominantly on north and north-east facing sites supporting Kirkby *et al*'s (1990) assertion that the densest vegetation will be found in these aspects. Aspects of classes 5, 4 and 3 move progressively around towards the north-west and landcover of classes 1 and 2 are to be found mainly facing between north-west and south-west.



a b

Figure 6.13 Rose diagrams of (a) aspect for all pixels and (b) class aspect percentage in the Mocatán catchment area

Examination of the 'All %' line in Figure 6.13(b) indicates that the majority of this subset lies in a north facing direction as south facing slopes are uncommon. To examine the strength of the relationship between classes and aspect, 'expected' values for the number of pixels in each class having each orientation were calculated as follows:

total number of pixels in that class * the percentage of all classes in each aspect/100.

The expected value calculated represented the number of pixels within a class that would be expected to have the aspect given the percentage with that aspect in the whole dataset (i.e. if all cover classes are simply a random selection from total pixel pool) as follows: e.g. for Class x west facing pixels : Total pixels in class x = 6488. In the full data set 16.01% of pixels face west, thus if Class x pixels were drawn at random from the total pixel pool 16.01% should face west (i.e. 16.01% of 6488 = 1039 pixels). Differences between observed and expected pixel numbers were standardised to a percentage as follows:

Observed-expected/expected*100

Table 6.8 displays the percentage differences for the Mocatán catchment. A negative percentage value indicates that the expected number of pixels in that aspect is higher than the observed number of pixels. A positive percentage value indicates that expected number of pixels in that aspect is lower than the observed. The greater the absolute value, the more the difference between observed and expected numbers of pixels in each aspect group.

	NDVI Class					
Aspect	Class 1	Class 2	Class 3	Class 4	Class 5	Class 6
N	-26.8	-18.7	1.0	27.2	60.7	58.9
NE	-16.6	-14.2	1.6	9.0	43.5	67.8
E	4.2	-0.4	8.4	-1.9	-19.0	-2.2
SE	25.8	17.3	-0.5	-33.7	-53.5	-39.0
S	46.6	21.2	-20.3	-48.1	-63.6	-64.1
SW	37.2	26.0	-20.2	-41.4	-59.1	-57.1
W	4.1	9.7	1.9	-5.4	-20.0	-31.1
NW	-20.0	-11.7	9.0	30.9	26.2	2.8

Table 6.8 Percentage deviation from expected (o-e/e*100) values for NDVI by aspect class in the Mocatán Catchment

As can be seen in Table 6.8, NDVI class is significantly associated with aspect in the Mocatán catchment where the sparser classes are found more often than expected facing south-east, south and south-west and the dense classes are found facing north and north-east more often than expected..

Chi square values were calculated for NDVI by aspect for both catchments and each subset, and showed very high levels of significance. These are reported at the end of this section where the significance of the association of aspect and class in both catchments and subsets is assessed.

6.6.1.2 NDVI and aspect in the Infierno catchment

The same methods as used with the Mocatán catchment image were applied to investigate aspect relationships in the Infierno catchment. A rose diagram of the pixel level distribution of aspect for the Infierno catchment is shown in Figure 6.14(a). The distribution of aspect in the Infierno catchment study area shows that most of the classes do not have many pixels facing between 180º and 270º, this is detailed in Figure 6.14 (b) which shows percentages plotted as a rose diagram.

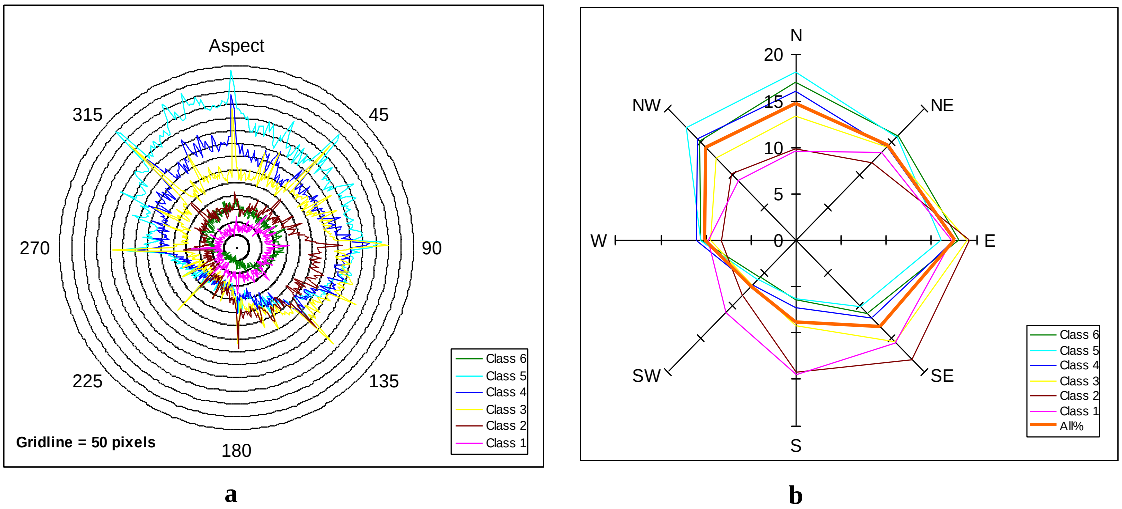


Figure 6.14 Rose diagrams of (a) aspect for all pixels and (b) class aspect percentage in the Infierno catchment

Classes 1 and 2 have a high percentage of pixels facing generally south, (90º 180º 270º). More than 70% of class 3 pixels face between 315º and 135º. Class 4 has a fairly even distribution of aspects for its pixels apart from in the range 180º and 225º. Almost 70% of the pixels in classes 5 and 6 lie between 315º and 90º, indicating that the more dense vegetation they contain is associated with areas receiving less solar radiation. South and south-west facing slopes are not common in this subset; the majority of aspects here lie within the range 315º to 135º (north-west to south-east) due to the orientation of the ridges and valleys (Figure 6.10).

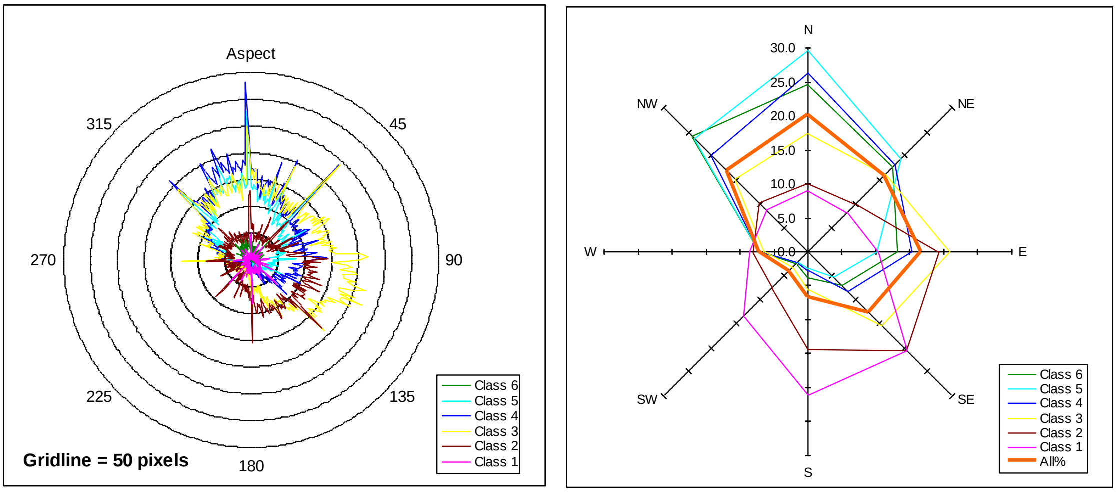
Percentage deviations from observed and expected values were calculated for this subset (Table 6.9). These figures show a trend for the sparse cover classes (1 to 3) to have greater numbers of pixels than expected facing south, south-west and south-east, and the denser cover classes (4 to 6) to have above expected values facing north, north-west and north-east. These results indicate a relationship between aspect and cover class in the Infierno catchment.

	NDVI class					
Aspect	Class 1	Class 2	Class 3	Class 4	Class 5	Class 6
N	-35.0	-33.4	-9.6	8.9	22.6	15.4
NE	-6.3	-18.4	-0.9	-0.8	9.6	11.2
E	-2.4	8.7	7.3	-1.3	-9.2	1.9
SE	17.6	36.9	16.2	-10.6	-23.6	-15.5
S	62.3	60.1	3.7	-17.6	-28.7	-28.0
SW	54.3	20.4	-1.9	-4.2	-14.7	-19.6
W	-3.6	-17.9	-5.9	9.6	5.5	5.5
NW	-34.9	-27.5	-10.7	9.5	22.0	8.3

Table 6.9 Percentage deviation from expected (o-e/e*100) values for NDVI by aspect class in the Infierno catchment

6.6.1.3 Aspect in the Malaguica subset of the clustered NDVI image

The rose diagram in figure 6.15(a) shows the aspect distribution in each class in the Malaguica subset of the NDVI image. The distribution of aspect shows that there are very few pixels of any class found between 180º and 290º. This distribution is related to the topography of the area as most of the land slopes away towards the north east and the channels run in a west to east or south-west to north-east direction. This leaves little opportunity for slopes to develop in a south-westerly or westerly direction. Figure 6.15(b) shows aspect percentages for each class and shows a considerable difference between classes 1 and 2 and classes 3 to 6. Aspect in classes 1 and 2 shows a markedly different pattern to that for all pixels and falls mainly between 90º and 225º, again indicating that the classes with least vegetation are the ones which, by position, are exposed to the most solar radiation. Class 3 comes in-between the sparse cover classes and the more dense cover classes with respect to aspect. Class 3 is associated with a wide range of aspects and can be found in double figure percentages from 315º to 135º indicating that this cover class is tolerant of fairly high amounts of solar radiation. Classes 4, 5 and 6 show a marked preference for north west, north, and north east facing slopes with only about 20% of these NDVI classes falling between 90º and 315º.



a b

Figure 6.15 Rose diagrams of (a) aspect for all pixels and (b) class aspect percentage in Malaguica

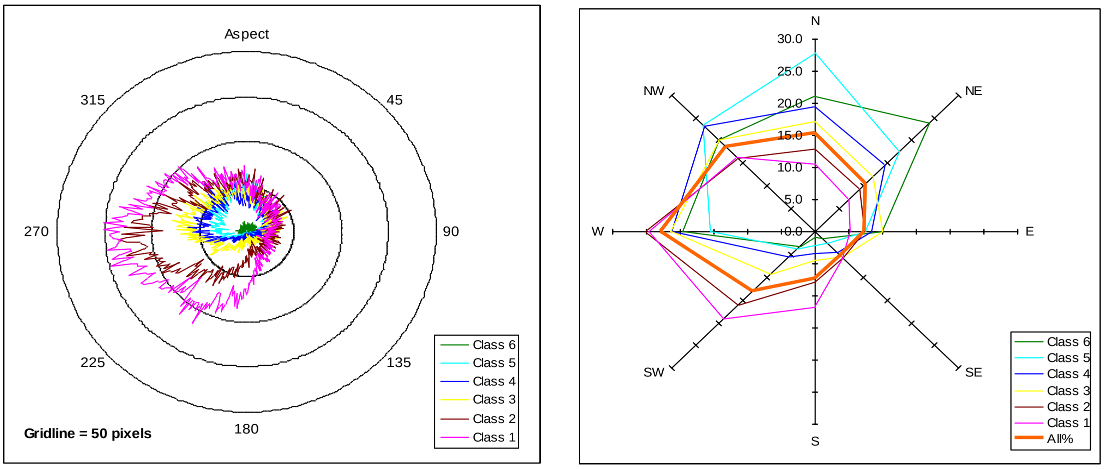
The percentage deviation figures (Table 6.10) indicate that the reality of the distribution of aspect in the classes is not what is expected. The percentage difference between observed and expected is very large between south-east and south-west. Figures here indicate that classes 1 and 2 are found with these aspects much more often than would be expected. Classes 4, 5 and 6 are more often found facing between north-east and north-west than would be expected although the percentage difference is not nearly as extreme as for classes 1 and 2. Aspect has appears to have a strong relationship with class distribution in this subset of the study area.

Aspect	NDVI Class Class 1	Class 2	Class 3	Class 4	Class 5	Class 6
N	-55.9	-50.5	-13.8	30.1	46.4	21.3
NE	-49.0	-36.8	2.9	14.6	23.2	12.3
E	-37.3	15.6	25.7	-8.3	-38.8	-21.0
SE	63.7	62.1	19.7	-35.8	-58.3	-45.9
S	220.4	119.5	-15.7	-58.3	-62.6	-40.1
SW	233.3	84.5	-19.2	-42.2	-43.7	-37.8
W	19.5	12.1	-10.3	0.6	0.0	0.6
NW	-48.7	-39.2	-11.1	18.0	39.6	42.7

Table 6.10 Percentage deviation from expected (o-e/e*100) values for NDVI by aspect class in Malaguica

6.6.1.4 Aspect in the Mocatán badland subset of the clustered NDVI image

Figure 6.16(a) shows a rose diagram illustrating aspect values for each pixel in each class for the Mocatán badland subset of the field area. Classes 1 to 4 in the Mocatán badland subs*et al*l have aspects which lie mostly between 225º and 315º with classes 1 and 2 having more pixels on the southern side of west and classes 3 and 4 having more pixels on the northern side of west. Class 5 has pixels lying between 270º and 45º indicating a more northerly aspect to this class. What little class 6 there is has pixels that are even more tightly clustered around a northerly orientation, and there is a sharp peak in the number of pixels facing between 0º and 45º. Figure 6.16(b) shows pixel aspect percentage value.



a b

Figure 6.16 Rose diagrams of (a) aspect for all pixels and (b) class aspect percentage in the Mocatán badlands

As can be seen in Figure 6.14(b) there is a progressive change from south facing to north-east facing in the respective aspects of the classes from 1 to 6. Class 1 has mainly south to west facing aspects, class 2 has south-west to west facing aspects. Class 3 has a slightly more even distribution of aspect and most closely mirrors the overall pattern. Class 4 has a similar distribution to class 5, but there are more of this class's pixels facing north-east than those of class 3. Class 5 has a definite north-west and north facing trend. Class 6 has a similar percentage of pixels (around 20%) facing from west to north-east. Table 6.11 shows the class aspect expected-observed percentage differences. It can be seen that aspect is strongly associated with the cover distribution. Classes 2 and 3 have less extreme percentage differences than the other four classes indicating that aspect is not as highly associated with these two classes. Classes 5 and 6 appear to be very associated with aspect as they have high positive figures for north, north-east and easterly facing positions.

	NDVI Class					
Aspect	Class 1	Class 2	Class 3	Class 4	Class 5	Class 6
N	-31.5	-16.1	11.8	27.0	81.6	37.1
NE	-35.5	-14.8	13.3	36.0	63.6	122.5
E	-29.6	0.5	38.3	17.1	3.9	37.9
SE	12.8	10.7	6.5	-11.3	-51.6	-70.5
S	61.8	7.9	-39.1	-54.5	-71.3	-87.9
SW	45.3	22.4	-27.9	-58.2	-71.6	-75.0
W	8.2	10.5	-6.0	-7.2	-31.7	-14.2
NW	-12.0	-13.2	8.3	24.9	26.3	8.5

Table 6.11 Percentage deviation from expected (o-e/e*100) values for NDVI by aspect class in the Mocatán badlands

6.6.1.5 Aspect and class in the Juan Contreras badlands subset

Figure 6.17(a) shows a rose diagram illustrating aspect values for each pixel in each class of the Juan Contreras badlands subset of the field area.

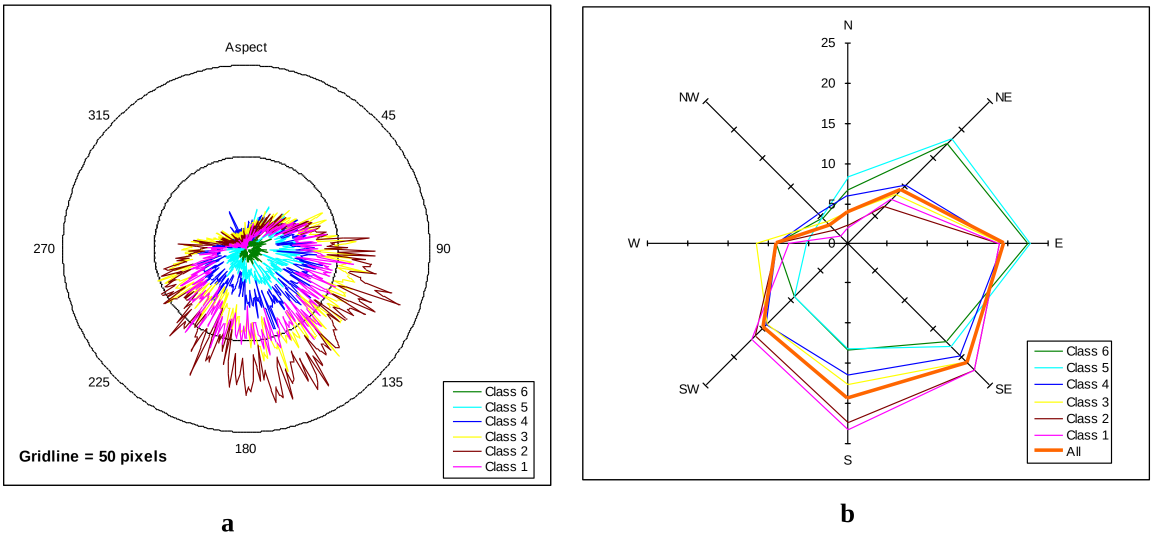


Figure 6.17 Rose diagrams of (a) aspect for all pixels and (b) class aspect percentage in the Juan Contreras badlands

It can be seen in fig 6.17(a) that the majority of all pixels in the Juan Contreras Badlands subset face between 70º and 240º. This distribution of aspect is obviously a function of the topography of this subset as it is taken from the north west side of the Barranco de los Contreras in the Infierno catchment. Figure 6.17(b) shows these percentages as a rose diagram. Classes 1 to 4 display a similar trend of aspect with the highest percentage of pixels facing south to south-east in all four classes.

Classes 5 and 6 have a slightly different trend in that the pixels in these classes mainly face south-east to north-east.

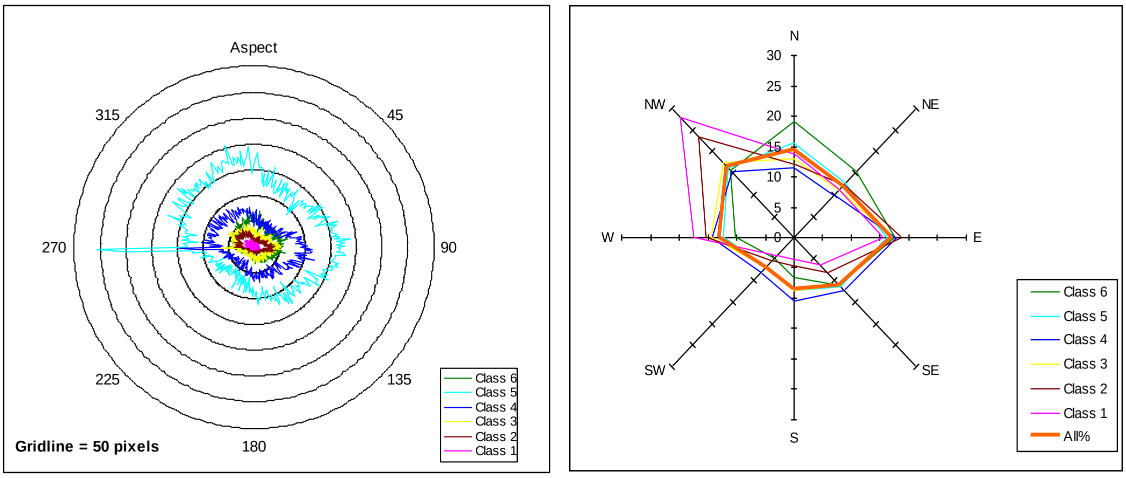
The observed and expected value percentage aspect differences (Table 6.12) for pixels in the Juan Contreras badlands indicate that there is some association of distribution of cover and aspect. Class 5 has high positive percentage difference for north and north-east facing pixels indicating a strong association between this class and aspect. Classes 1 to 4 have lower values than classes 5 and 6 indicating that these classes are not as strongly associated with aspect.

	NDVI Class					
Aspect	Class 1	Class 2	Class 3	Class 4	Class 5	Class 6
N	-49.2	-42.8	1.6	52.6	113.8	72.7
NE	-15.2	-30.7	-7.2	9.6	97.1	88.4
E	-3.2	-3.9	-1.0	-1.3	16.8	14.9
SE	5.5	6.0	-0.5	-6.1	-13.8	-17.9
S	20.3	15.3	-8.5	-15.3	-32.0	-30.9
SW	15.1	10.5	-4.3	-3.0	-36.0	-36.5
W	-16.9	0.3	28.4	0.6	-42.3	0.7
NW	-59.2	-31.4	21.2	62.0	45.8	35.9

Table 6.12 Percentage deviation from expected (o-e/e*100) values for NDVI by aspect class in the Juan Contreras badlands subset

6.6.1.6 Aspect and class in the Sorbas subset

Figure 6.18(a) shows a rose diagram illustrating aspect values for each pixel in each class of the Sorbas subset of the field area. Each class appears to have fairly even aspect distribution with slightly more pixels falling between 90º and 180º, and 270º and 360º than between 0º and 90º, and 180º and 270º. Classes 4 and 5 also have steep peaks at around 270º which could be caused by an anomaly in the DEM. Figure 6.18(b) shows aspect percentage figures for each class as a rose diagram.



a b

Figure 6.18(a) Rose diagram of aspect for all pixels in the Sorbas subset (b) rose diagram of class aspect percentage in the Sorbas subset

Classes 1 and 2 show a similar pattern both having a peak in pixel percentage facing north-west. Classes 3 and 4 follow a similar pattern which is fairly evenly distributed, peaking at 90º. The majority of class 5 is found between 315º and 90º, thus in the more northerly facing areas. Class 6 is also found mainly between these aspects, but is also more commonly found on south and south-west and west facing slopes than class 5.

The observed and expected percentage difference values for the pixels (Table 6.13) indicate that there is some association between aspect and pixel class. The percentage differences for classes 1 and 2 show more aspect association than classes 4 to 6. Classes 3 and 5 in particular have very small percentage differences between observed and expected pixel values indicating that these two classes are unassociated with aspect.

	NDVI Class					
Aspect	Class 1	Class 2	Class 3	Class 4	Class 5	Class 6
N	-4.2	-16.7	-10.9	-20.7	6.9	31.5
NE	-7.2	0.9	-8.3	-17.6	4.2	25.0
E	-8.8	10.8	0.6	4.9	-4.6	3.1
SE	-44.2	-29.0	-1.7	9.3	1.7	-0.3
S	-57.6	-45.2	2.1	23.3	2.5	-22.4
SW	-38.4	-17.5	3.2	20.6	1.7	-32.1
W	33.5	16.5	11.4	9.3	-5.1	-21.7
NW	66.4	39.7	4.9	-7.8	-3.5	-7.4

Table 6.13 Percentage deviation from expected (o-e/e*100) values for NDVI by aspect class in the Sorbas subset

6.6.2 NDVI and aspect summary

Chi Square tests were carried out on the aspect data for all classes in both catchments and all four subsets. All Chi Square results were significant at the 0.01 level. The chi-scores for each class for all aspects in all subsets have been plotted on a single graph to indicate which classes have higher Chi Square values and so are more associated with aspect (Figure 6.19).

Comparing the catchments, class 1 is highly associated with aspect in the Mocatán catchment. In the Infierno catchment, classes 1 and 2 are strongly associated with aspect. Classes 1 and 2 are sparsely vegetated classes and are found facing in a southerly direction more often than would be expected. It would appear, therefore, that these sparsely vegetated areas are directly associated with aspect. Class 5 is also found to be strongly associated with aspect in the Mocatán and Infierno catchments with its pixels facing north more often than expected. Class 5 is made up of dense shrubby cover. Thus it appears that dense plant cover is associated with northerly aspects in both catchments of the study area.

Classes 3, 4 and 6 do not seem to be as strongly associated with aspect as classes 1, 2 and 5. Classes 3 and 4 are intermediately vegetated classes. It appears that these cover types are more ubiquitous and can and do grow on sites with aspects between 1 and 360°. Their distribution may be affected by environmental variables other than aspect. It could be hypothesised that class 6 which is more dense than class 5 would prefer north-facing sites, but the Chi Square scores indicate otherwise. This low Chi Square score may be related to the lower amount of class 6 throughout both catchments relative to the other five classes. However, the distribution of this very dense cover type could very well be related to another environmental variable.

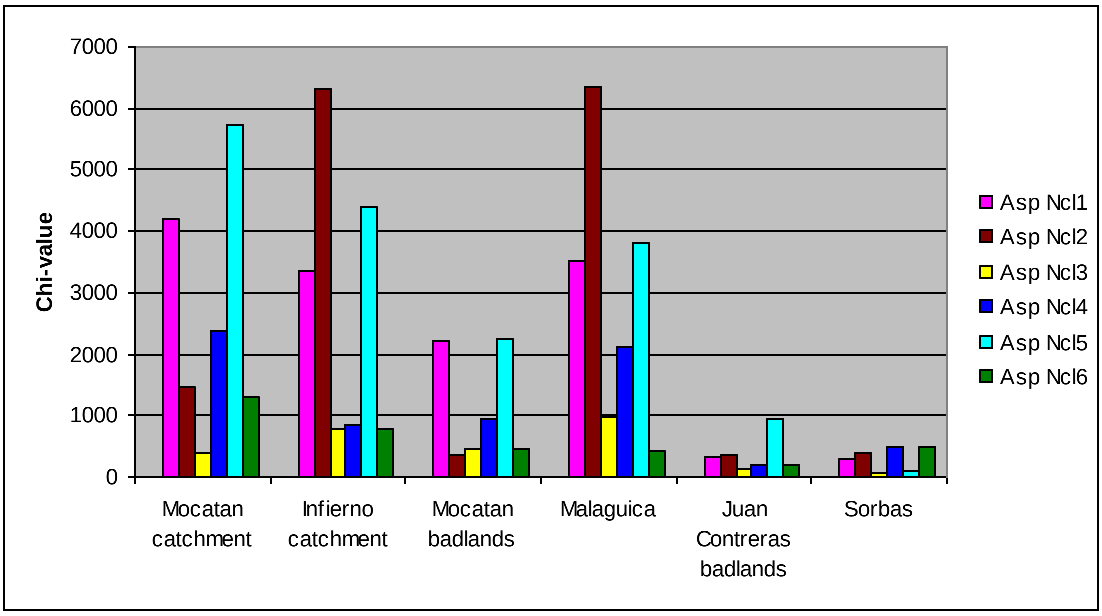


Figure 6.19 Bar graph showing aspect Chi Square values for each class in all subsets

The four subsets show a great variability with regard to aspect Chi Square scores. Cover patterns in Malaguica appear to be most associated with aspect out of the four subsets with classes 1, 2 and 4 having high Chi Square scores. Cover pattern in the Mocatán badlands also seems to be associated with aspect, although less so than Malaguica, and less so than in the Mocatán catchment as a whole. The Juan Contreras badlands and the Sorbas subsets have much lower Chi Square values for all classes than any of the other subsets. The lower level of association of class with aspect in the Juan Contreras badlands is, as mentioned before, likely to be a function of topography. The lower association between class and aspect in the Sorbas subset indicates another environmental variable being more responsible for cover distribution.

6.6.3 Clustered NDVI image and slope

The aim of investigating the study area slope data was to discover if there were any relationships between landcover as described by the clustered NDVI image and slope. Slope statistics (from 0 to 90º) are available for each pixel of the aspect image of the study area. Using ERDAS Imagine, the 'mask' routine was again used to extract slope data for each of the six classes of the clustered NDVI image. The area of the class of interest from the clustered NDVI image is used to collect data from the aspect image so that only data in the area of interest (i.e. the area which that class covers) is collected. This means that pixel statistics for just class x can be viewed which enables analysis of slope vs. class to be carried out.

6.6.3.1 NDVI and slope in the Mocatán catchment

Figure 6.20 shows percentage occurrence of pixels of each NDVI class in each slope category. Pixel percentage has been used to display the information rather than pixel numbers as differences in class pixel distribution patterns are demonstrated more concisely in this way.

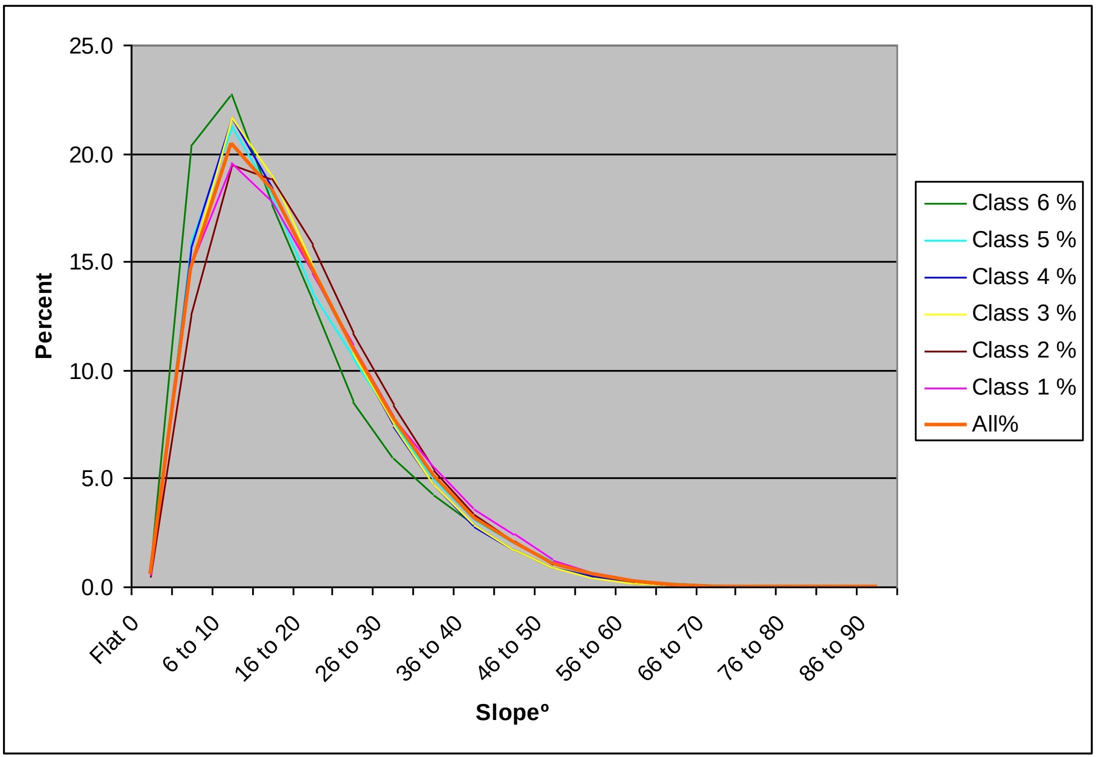


Figure 6.20 Slope pixel percentage by NDVI class in the Mocatán Catchment

There are similarities in slope distribution in most of the classes. Class 6 varies most from the average for all classes. A similar technique for investigation of the slope data to that used for examination of aspect variation by class was used, that of percentage difference between observed and expected pixel numbers. However, some amalgamation of slope groups was necessary since the very low number of pixels with higher slope values gave exceedingly high percentage differences between observed and expected (for instance if the expected value was three pixels and the observed value was nine pixels then a percentage difference of 200% would be derived). These groups are shown in Table 6.14.

There are some small percentage differences between observed and expected pixel numbers. However, the magnitude of the differences are much smaller than between observed and expected pixel numbers for aspect. Class 6 has the largest percentage difference between observed and expected pixel values and this class is found more frequently on gentle slopes and less frequently on steep slopes than would be expected. Class 1 is found more often on steep slopes than would be expected. In general there is some variation from the expected in the Mocatán catchment, but this variation is not great.

Slope°	Class 1	Class 2	Class 3	Class 4	Class 5	Class 6
	NDVI Class					
Flat to 5	1.1	-14.6	1.8	6.9	8.5	39.9
6 to 10	-4.4	-4.8	5.9	5.8	3.7	10.8
11 to 15	-3.2	2.9	3.3	0.1	-1.9	-4.0
16 to 20	-1.8	7.0	0.8	-0.9	-7.7	-10.2
21 to 15	0.7	5.6	-1.9	-1.4	-4.2	-22.5
26 to 30	0.9	7.9	-3.7	-4.8	-2.7	-23.9
31 to 35	7.8	4.2	-8.6	-8.0	-3.0	-18.0
36 to 40	11.6	4.9	-12.4	-13.7	-3.8	-11.9
above 40	16.2	1.6	-21.5	-18.6	9.7	-10.5

Table 6.14 Percentage deviation from expected (o-e/e*100) values for NDVI by slope class in the Mocatán catchment

6.6.3.2 NDVI and slope in the Infierno catchment

Figure 6.21 shows the percentage of pixels in each slope category. Class 1 shows a distinct difference in the distribution of pixels from the average pixel distribution in this catchment. The percentage differences between observed and expected pixel distribution in the Infierno catchment are shown in Table 6.15.

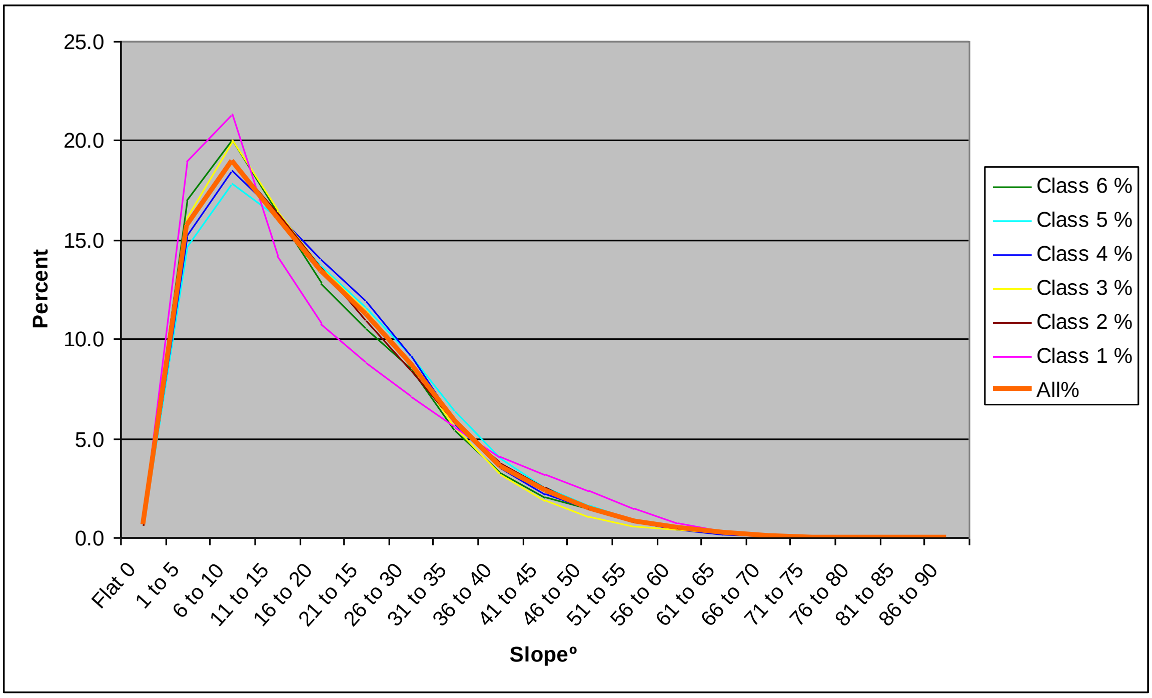


Figure 6.21 Slope pixel percentage by NDVI class in the Infierno catchment

It can be seen that class 1 varies most from the expected distribution (Table 6.15). Class 1 is found more commonly on very gentle and very steep slopes than on intermediate slopes. The dichotomy of class 1's distribution could be explained by the fact that the flat class 1 areas are often bare agricultural terraces and the steep slopes are likely to be areas of erosion. Class 3 appears to be associated with gently sloping areas and is found less on steep slopes than would be expected. Class 5 is found more often on steep slopes than would be expected. Class 6 is again more associated with flat and gently sloping areas than steep slopes.

Slope°	NDVI Class Class 1	Class 2	Class 3	Class 4	Class 5	Class 6
Flat to 5	21.6	0.5	2.1	-3.7	-7.0	9.0
6 to 10	12.3	-0.1	5.4	-2.9	-6.3	5.5
11 to 15	-12.0	1.4	1.9	0.8	-0.1	0.8
16 to 20	-20.2	1.0	1.3	4.2	1.6	-4.6
21 to 15	-21.8	-2.8	1.5	6.0	3.0	-6.6
26 to 30	-18.4	-4.3	-0.5	4.6	4.4	-3.2
31 to 35	-5.1	-0.3	-4.5	-2.1	8.7	-7.4
36 to 40	13.4	4.0	-11.6	-3.9	9.4	-10.1
above 40	47.4	2.5	-23.4	-6.5	10.3	-3.8

Table 6.15 Percentage deviation from expected (o-e/e*100) values for NDVI by slope class in the Infierno catchment

6.6.3.3 NDVI and slope in Malaguica

Figure 6.22 shows the percentage of NDVI class pixels in each slope category. Slope distribution between classes shows more variation in this subset than across the Infierno or Mocatán catchments. Table 6.16 shows the percentage variation between observed and expected pixel values for the classes in this subset.

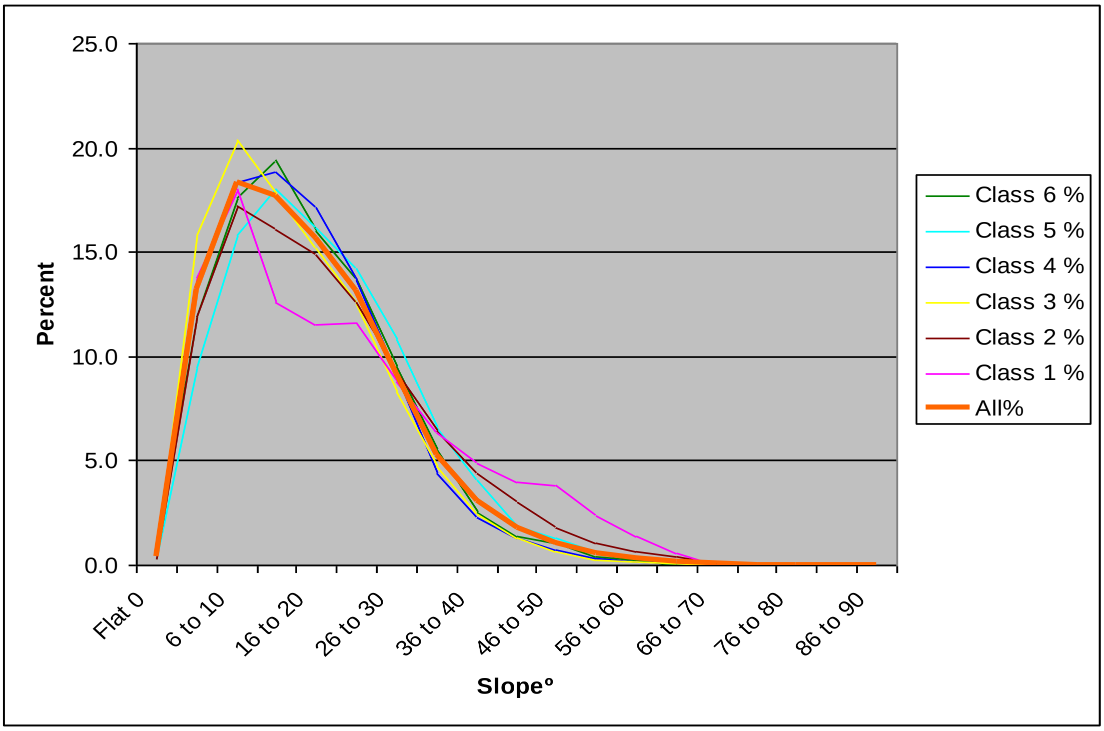


Figure 6.22 Slope pixel percentage by NDVI class in Malaguica

There is more variation in the percentage difference between observed and expected values in this subset than in the two catchments as a whole. In particular, class 1 shows a very large variation in the slope values. Class 1 is highly associated with steep slopes in this subset and classes 2 and 5 are also associated with steep slopes although not as highly as class 1. Classes 3 and 4 have negative associations with steep slopes, but this does not translate into a strong association with gentle slopes.

Class 6 is found to be more associated with intermediate slope values, and is negatively associated both with very gentle and very steep slopes.

Slope°	NDVI Class Class 1	Class 2	Class 3	Class 4	Class 5	Class 6
Flat to 5	4.7	-10.2	19.5	1.0	-28.2	-6.7
6 to 10	-1.8	-6.3	11.1	-0.1	-13.7	-4.2
11 to 15	-29.1	-9.2	0.5	6.5	1.8	9.6
16 to 20	-26.6	-5.2	-3.5	9.2	2.8	1.7
21 to 15	-11.5	-3.9	-4.6	4.0	8.4	4.4
26 to 30	-4.2	1.3	-9.3	-0.6	17.7	3.7
31 to 35	19.7	20.4	-12.1	-17.9	23.6	3.9
36 to 40	55.8	40.3	-20.6	-26.5	30.8	-18.4
above 40	205.7	76.8	-38.0	-35.3	17.2	-21.5

Table 6.16 Percentage deviation from expected (o-e/e*100) values for NDVI by slope class in Malaguica

6.6.3.4 NDVI and slope in the Mocatán badlands

Figure 6.23 shows the percentage of pixels of each NDVI class in each slope category in the Mocatán badlands subset. There is quite a lot of variation around the mean percentage. This is demonstrated by looking at the observed and expected percentage variation (Table 6.17).

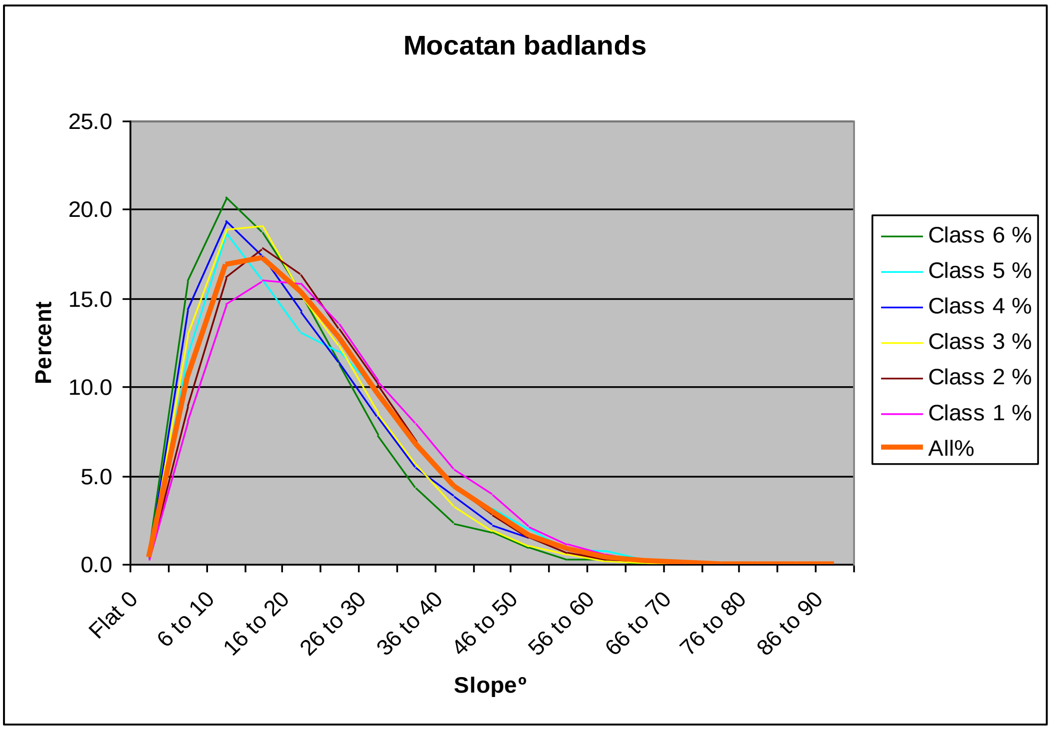


Figure 6.23 Slope pixel percentage by NDVI class in Mocatán badlands

It can be seen that NDVI class 1 pixels are negatively associated with flat areas and positively associated with steeper areas. There is a relationship between the steepness of the slope and class 1. Classes 3 and 4 are positively associated with flat and gently sloping areas and progressively more negatively associated with steeper slopes. Class 6 is highly positively associated with flat and very gentle slopes and highly negatively associated with medium to steep slopes. Class 5 shows a highly variable percentage difference between observed and expected slope pixel counts, and appears to be associated with gentle and very steep slopes.

	NDVI Class					
Slope°	Class 1	Class 2	Class 3	Class 4	Class 5	Class 6
Flat to 5	-22.9	-13.8	24.3	38.8	12.2	56.7
6 to 10	-13.1	-3.9	11.9	14.7	10.6	22.2
11 to 15	-6.8	3.5	10.5	0.9	-6.7	8.9
16 to 20	3.0	6.5	-1.3	-7.3	-14.7	-0.2
21 to 15	5.8	3.5	-3.9	-10.8	-5.7	-12.3
26 to 30	7.0	5.9	-11.7	-13.5	1.9	-24.0
31 to 35	16.7	1.6	-17.2	-19.2	0.0	-37.3
36 to 40	21.5	0.8	-26.5	-13.5	-3.1	-48.9
above 40	31.5	-9.9	-37.7	-18.8	16.1	-46.4

Table 6.17 Percentage deviation from expected (o-e/e*100) values for NDVI by slope class in the Mocatán badlands

6.6.3.5 NDVI and slope in the Juan Contreras badlands

Figure 6.24 shows the variation of class distribution by slope. There is wide variation in the class distributions, with classes 1, 5 and 6 in particular showing a marked difference when compared to the average distribution. These differences are demonstrated by the observed-expected percentage difference values for each class (Table 6.18).

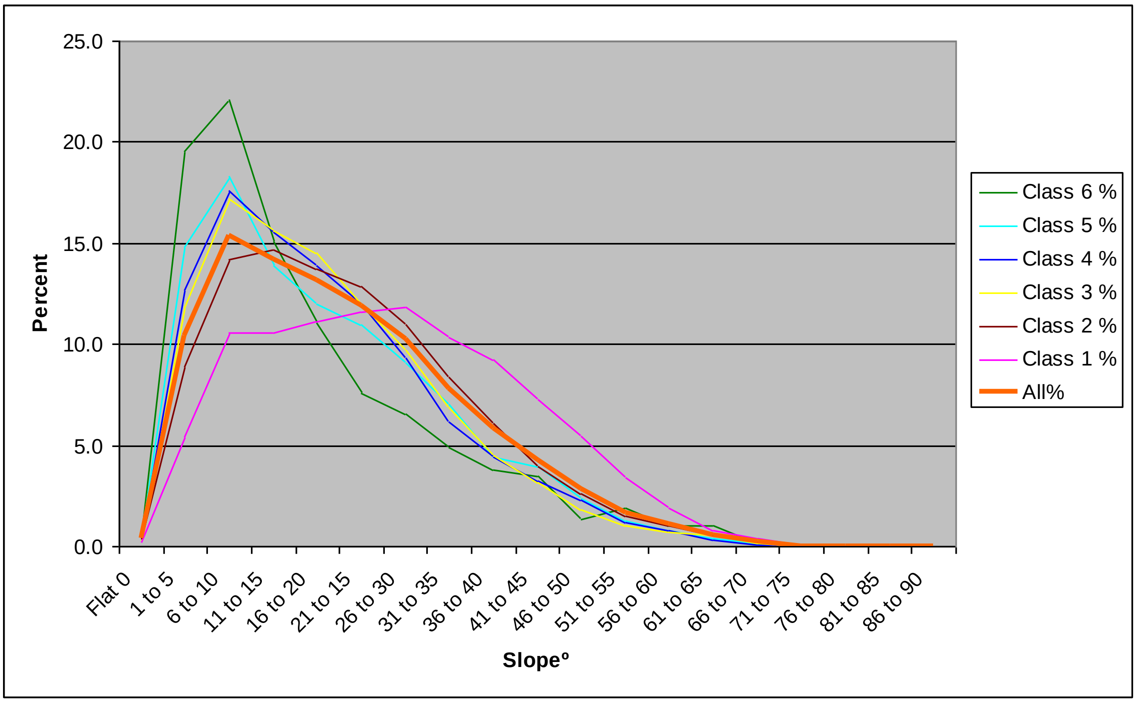


Figure 6.24 Slope pixel percentage by NDVI class in the Juan Contreras badlands

Slope°	NDVI Class Class 1	Class 2	Class 3	Class 4	Class 5	Class 6
Flat to 5	-47.4	-14.1	12.5	21.8	42.8	85.5
6 to 10	-31.4	-7.7	11.6	14.5	18.8	43.6
11 to 15	-25.8	3.2	10.3	9.6	-2.0	6.4
16 to 20	-15.9	3.9	10.0	4.9	-9.0	-16.3
21 to 15	-2.8	7.6	0.5	0.3	-8.1	-36.3
26 to 30	15.4	7.0	-5.7	-9.2	-11.3	-36.3
31 to 35	32.5	7.2	-11.8	-21.1	-10.4	-37.4
36 to 40	58.5	4.9	-22.2	-23.8	-24.4	-35.4
above 40	80.3	-7.0	-29.9	-25.1	-16.0	-15.9

Table 6.18 Percentage deviation from expected (o-e/e*100) values for NDVI by slope class in the Juan Contreras badlands

Class 1 shows a marked association with steep slopes. There is a direct relationship between steepness of slope and percentage difference values in this class with the largest negative class 1 values being flat to 5° and the largest positive percentage difference value being slopes above 40°. Classes 3 and 4 show a positive association between gentle slopes and this type of cover and progressively more negative associations as slopes steepen. Classes 5 and 6 have strong positive associations with flat and gentle slopes and negative associations with steep slopes, class 6 having a stronger negative association with these slope categories than class 5.

6.6.3.6 NDVI and slope in the Sorbas subset

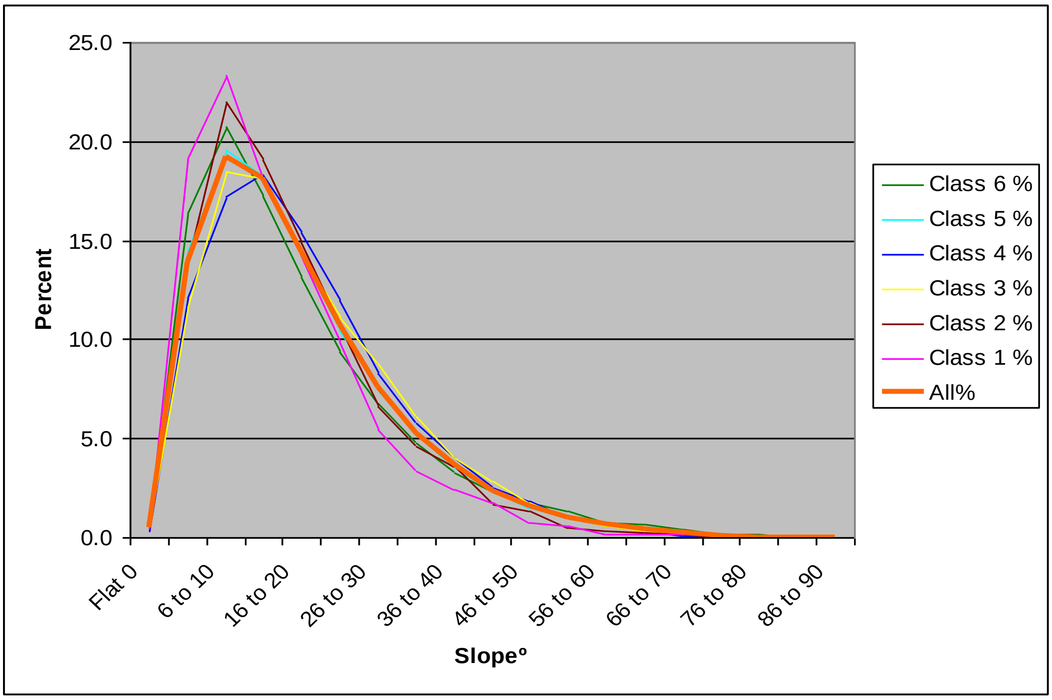


Figure 6.25 Slope pixel percentage by NDVI class in the Sorbas subset

The NDVI classes in the Sorbas subset show values which conform more to the average overall value than was the case with the other three catchment subsets (Figure 6.25). The greatest variation from the expected slope is found in class 1 where it is more associated with flat and gentle slopes than it is with steep slopes (Table 6.19). Classes 3 and 4 are more associated with steep slopes than the other classes except for class 6 which has a positive association both with flat and gentle slope, and the steepest slope category. It is likely that class 1 is associated with gentle slopes. In the Sorbas subset, the little class 1 that can be found is associated with a road and with agricultural terraces. The surfaces of these are flat, thus accounting for the association between class 1 and gentle slopes.

	NDVI Class					
Slope°	Class 1	Class 2	Class 3	Class 4	Class 5	Class 6
Flat to 5	35.7	-0.6	-15.1	-13.6	4.2	18.1
6 to 10	21.0	14.1	-4.1	-10.5	1.5	7.5
11 to 15	-0.4	4.9	-0.1	1.1	0.3	-5.3
16 to 20	-1.7	3.2	-0.5	6.8	-1.4	-8.7
21 to 15	-8.0	-0.5	3.6	11.4	-2.9	-12.5
26 to 30	-28.5	-13.5	15.4	8.9	-2.3	-10.4
31 to 35	-36.2	-12.9	15.0	9.4	-2.4	-9.9
36 to 40	-33.3	-2.4	11.0	10.7	-3.7	-9.9
above 40	-42.3	-32.9	5.1	0.5	-0.1	18.1

Table 6.19 Percentage deviation from expected (o-e/e*100) values for NDVI by slope class in the Sorbas subset

6.6.4 NDVI and slope summary

Chi Square tests were carried out on the slope data for all classes in all subsets. All Chi Square values were found to be significant at the 0.01 level. The Chi Square values for each class for all slope categories in all subsets were plotted on a single graph to facilitate comparison and identify those classes most likely to be associated with slope (figure 6.26). The Mocatán catchment does not have any classes with strong associations with slope. Classes 2 and 6 have the strongest associations with slope in this catchment, class 6 favouring gentle slopes, and class 2 showing a negative association with gentle slopes. In the Infierno catchment the Chi Square values are higher than those for Mocatán for all classes except 2. Class 1 is particularly strongly associated with slope, however it covers only a small percentage of the Infierno catchment, and is found as bare agricultural terraces or as the gypsum covered road, both flat areas, or on slopes in the steep Juan Contreras badlands area. This distribution indicates that class 1 is found in flat areas due to human intervention in the landscape, or more naturally, on steep sided erosional features. Class 5 in the Infierno catchment is associated with steep slopes. As in the Mocatán catchment class 6 is associated with flat areas. Class 3 is also associated with gently sloping ground and negatively associated with steep slopes.

Class 1 is strongly associated with steep slopes in both the Mocatán badlands and the Juan Contreras badlands. This distribution relates to the large expanses of bare TRU sediment exposed as badlands in both of these subsets. Classes 3 and 4 have higher Chi Square values than 2, 5 and 6 in the Mocatán badlands and are positively associated with gentle slopes. This cover distribution is likely to be associated with partially vegetated agricultural terrace bottoms and recolonised pediment slopes.

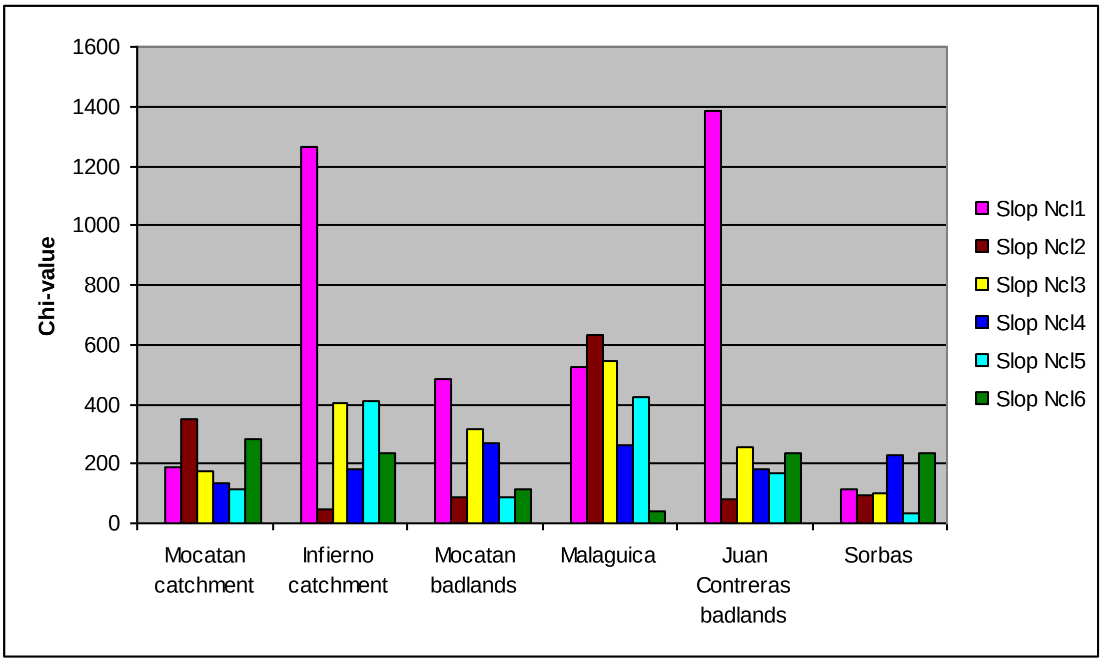


Figure 6.26 Slope Chi Square values for each class in all subsets

The strong association of classes 1 and 2 with steep slopes in the Malaguica is likely be related to areas of erosion and bare sediment. This subset contains a bare cliff about 50m in height which is likely to be contributing factor to the steep distribution of the bare classes. The Sorbas subset does not have any high Chi Square values for any of the cover classes. Class 6 is the most associated with aspect, and again, is associated with flat land or gentle slopes in this area.

6.6.5 NDVI and wetness index

As discussed in chapter 4, the wetness index indicates the upstream contributing area for each pixel. It was hypothesised that pixels which have more contributing area will have higher soil moisture content and therefore be able to support more vegetation. The wetness index image produced had 13 categories of wetness, category 1 having least upstream contributing area and category 13 having most upstream contributing area. These categories, which are equal divisions of wetness, were produced by ERDAS Imagine. Subsets of all six areas of interest were made from the wetness index image of the study area using ERDAS Imagine. As with aspect and slope, each of these subsets was then masked by class to produce statistics for analysis.

6.6.5.1 NDVI and wetness index in the Mocatán catchment

Figure 6.27 shows the distribution of wetness by class in the Mocatán catchment. Table 6.20 shows the observed and expected value percentage difference for wetness. Wetness categories 9 to 13 were amalgamated, as there were so few pixels in some of these classes that very large percentage figures were created by carrying out the percentage difference operation.

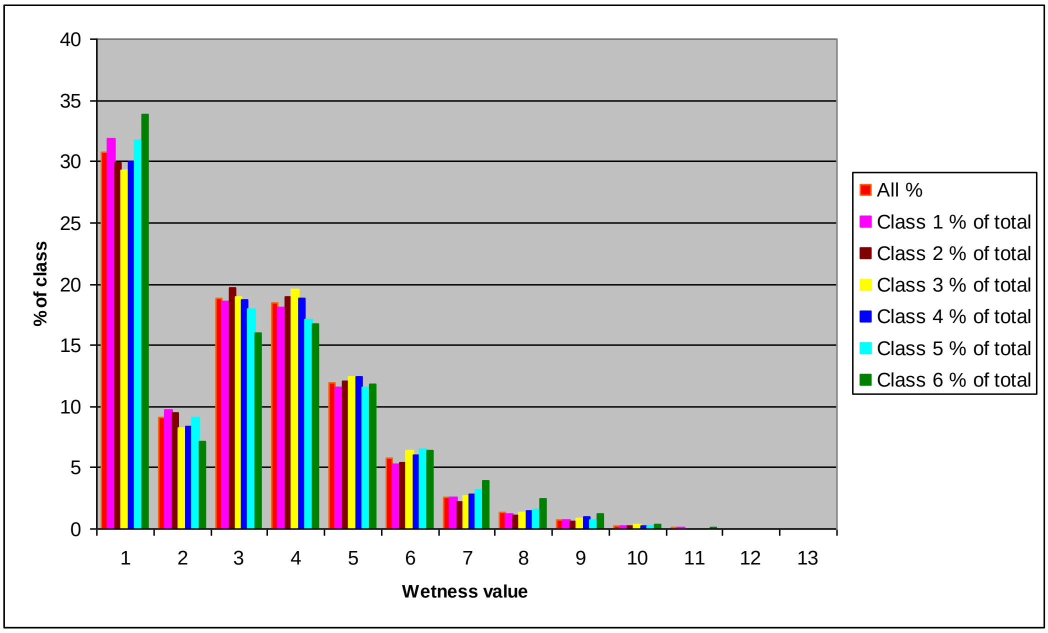


Figure 6.27 Percentage of NDVI pixels by class falling in each wetness category in the Mocatán catchment

The sparse cover classes 1, 2 and 3 have a negative association with increasing wetness. Classes 4, 5 and 6 which have denser cover have high positive associations with increasing wetness. Class 6 in particular, the densest cover class, has much higher wetness values than the other 5 classes.

Wetness value	Class 1	Class 2	Class 3	Class 4	Class 5	Class 6
1	3.7	-2.6	-4.9	-2.3	3.4	9.9
2	7.1	4.5	-9.7	-7.9	0.2	-21.4
3	-1.1	4.8	0.7	-0.3	-4.5	-14.9
4	-2.3	2.7	5.5	1.5	-7.3	-9.3
5	-3.6	1.0	4.4	3.7	-3.0	-1.3
6	-9.3	-6.5	11.5	5.2	12.9	9.7
7	-3.8	-14.5	1.2	6.1	19.9	49.8
8	-7.5	-16.8	-1.2	9.8	24.2	89.4
9 to 13	1.4	-11.9	3.5	13.4	-9.1	45.8

Table 6.20 Percentage deviation from expected (o-e/e*100) values for NDVI by wetness pixels in the Mocatán catchment

6.6.5.2 NDVI and wetness index in the Infierno catchment

Figure 6.28 shows the distribution of wetness index categories by class in the Infierno catchment. Table 6.21 shows the observed and expected value percentage difference for wetness.

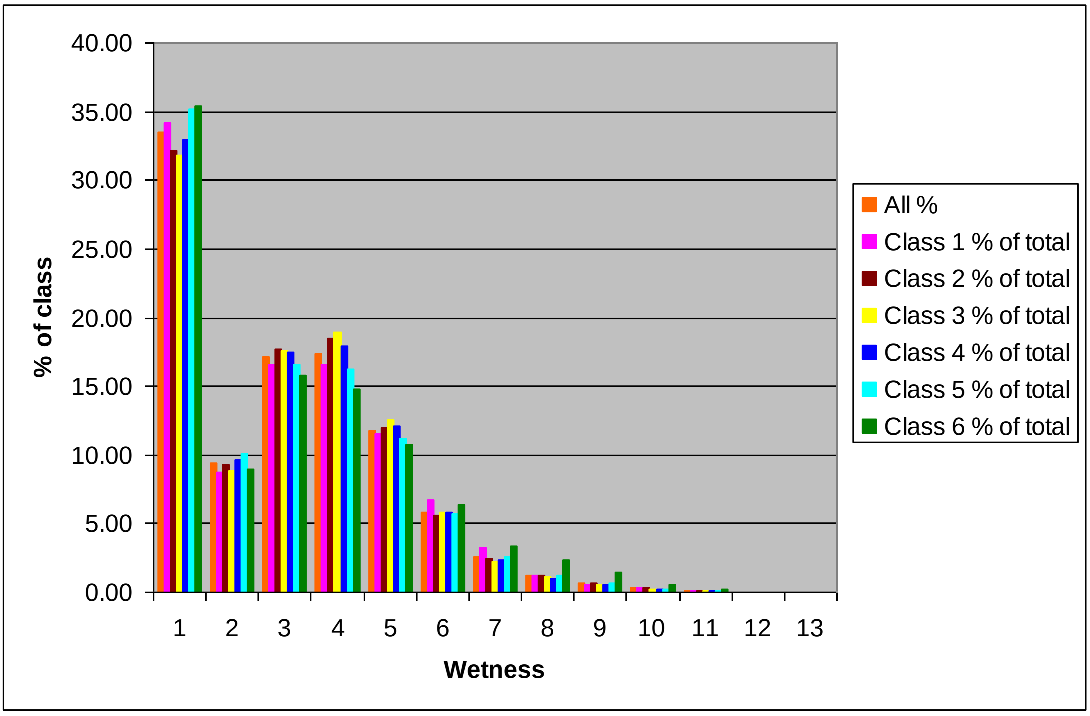


Figure 6.28 Percentage of NDVI pixels by class falling in each wetness category in the Infierno catchment

The percentage difference between observed and expected wetness values varies with class. The only class that shows a strong association with wetness is class 6 which has association with high wetness values. Class 1 also has quite a strong positive association with wetness categories 6 and 7.

Wetness value	NDVI Class					
	Class 1	Class 2	Class 3	Class 4	Class 5	Class 6
1	2.2	-4.1	-4.9	-1.7	5.0	5.7
2	-7.1	-1.9	-5.8	1.7	7.4	-5.0
3	-3.0	3.4	2.9	2.3	-2.9	-7.5
4	-4.5	6.2	8.7	2.8	-6.4	-15.2
5	-2.3	1.3	6.7	2.6	-4.7	-8.5
6	15.2	-4.5	-0.7	-1.2	-2.4	8.1
7	26.6	-1.1	-11.0	-8.7	0.2	29.9
8	-1.5	-2.8	-9.6	-19.7	-1.3	86.5
9 to 13	-3.0	6.3	-15.8	-21.0	-6.1	105.6

Table 6.21 Percentage deviation from expected (o-e/e*100) values for NDVI by wetness pixels in the Infierno catchment

6.6.5.3 NDVI and wetness index in Malaguica

Figure 6.29 shows the percent of each class in each wetness category in Malaguica. Table 6.22 shows the percentage difference between the observed and expected wetness values for this subset.

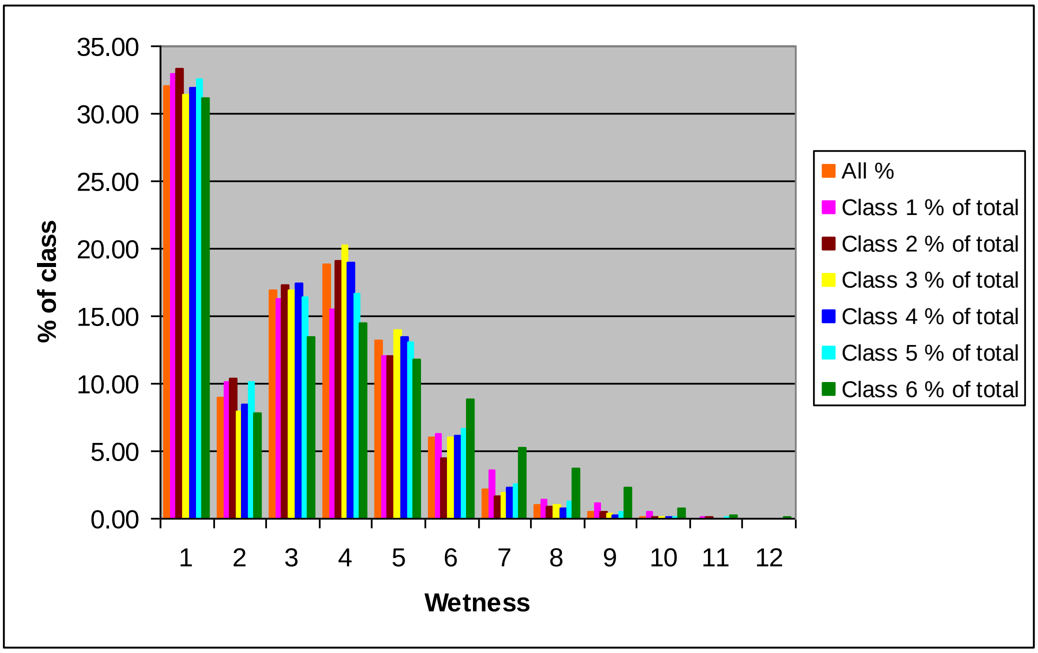


Figure 6.29 Percentage of NDVI pixels by class falling in each wetness category in Malaguica

Class 6 has a very large positive association with high wetness values in this subset which indicates that this class is found in places at the end of slopes where water drains to. Class 1 also has a large positive association with high wetness values. Class 2 is found to be positively associated with low wetness values. Classes 3 and 4 show positive associations with the middle wetness values and negative association with the lowest and highest wetness values. Class 5 has a mixture of positive and negative associations with all wetness values, not showing any obvious patterns indicating that this class is found in areas with both small and large cumulative drainage areas.

Wetness value	NDVI Class					
	Class 1	Class 2	Class 3	Class 4	Class 5	Class 6
1	2.5	3.8	-2.2	-0.5	1.2	-2.8
2	14.1	15.8	-10.9	-5.2	13.0	-12.7
3	-3.6	2.2	0.2	3.1	-2.8	-20.6
4	-17.8	1.7	7.2	0.9	-11.4	-23.2
5	-8.8	-8.8	5.7	1.7	-1.3	-11.0
6	5.6	-24.7	1.0	3.0	10.8	48.0
7	60.9	-26.0	-15.1	4.8	18.4	138.9
8	34.3	-18.6	-7.1	-26.7	18.4	257.0
9 to 13	142.0	8.9	-19.5	-42.1	-1.8	380.2

Table 6.22 Percentage deviation from expected (o-e/e*100) values for NDVI by wetness pixels in Malaguica

6.6.5.4 NDVI and wetness index in the Mocatán badlands

Figure 6.30 shows the percent of each class in each wetness category in the Mocatán badlands. Table 6.23 shows the percentage difference between the observed and expected wetness values for this subset.

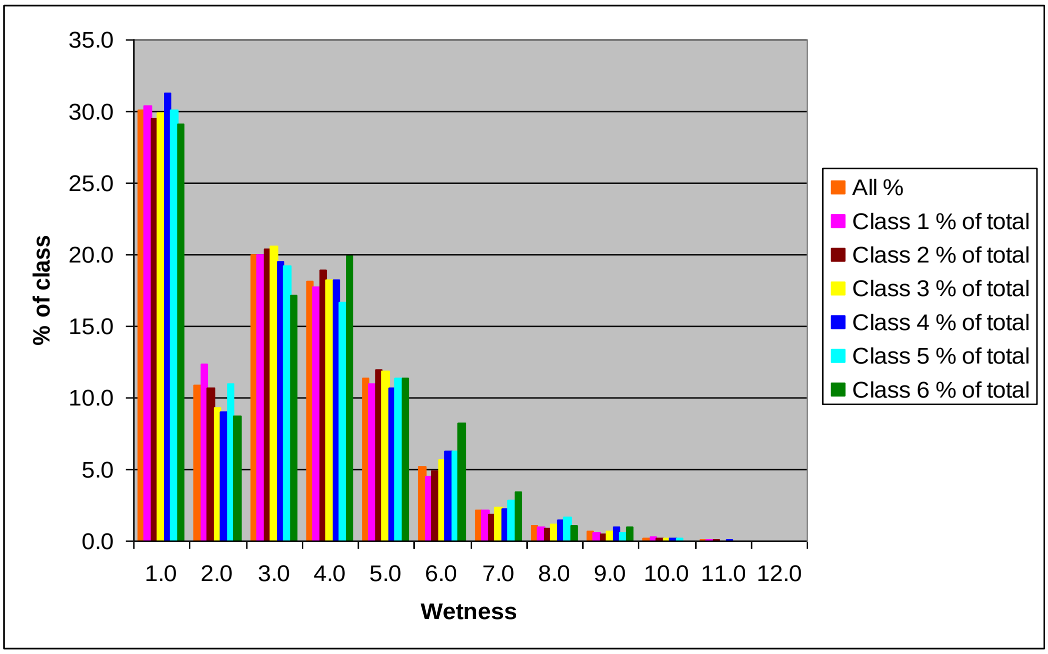


Figure 6.30 Percentage of NDVI pixels by class falling in each wetness category in Mocatán badlands

Class 1 in mainly positively associated with the lower wetness values. However it also has a positive association with values 9 to 13. Class 2 is positively associated with the middle wetness categories. Classes 3, 4, 5 and 6 are positively associated with the higher wetness categories, although class 5 has quite a strong negative association with the highest wetness values. The pattern of classes 5 and 6 can probably be explained by the fact that these classes are found on and around the Cerro de Juan Contreras ridge, and so do not have sufficient slope length to give a high wetness value.

Wetness value	NDVI Class					
	Class 1	Class 2	Class 3	Class 4	Class 5	Class 6
1	0.9	-2.0	-0.7	3.7	-0.2	-3.3
2	12.9	-2.1	-14.5	-17.3	0.6	-19.7
3	0.0	1.8	2.8	-2.6	-3.9	-14.5
4	-2.2	4.6	0.9	1.0	-7.8	10.1
5	-3.7	5.0	4.2	-5.9	0.1	0.2
6	-13.6	-5.2	8.5	19.8	20.7	58.2
7	-3.9	-14.2	5.1	3.7	31.4	56.9
8	-11.3	-17.4	1.5	29.9	52.8	-6.3
9 to 13	5.2	-15.0	3.4	36.0	-20.5	-2.6

Table 6.23 Percentage deviation from expected (o-e/e*100) values for NDVI by wetness pixels in the Mocatán badlands

6.6.5.5 NDVI and wetness index in the Juan Contreras badlands

The percentage of NDVI class pixels for each wetness category is shown in Figure 6.31. Table 6.24 shows the percentage difference between observed and expected number of pixels in each class in wetness categories.

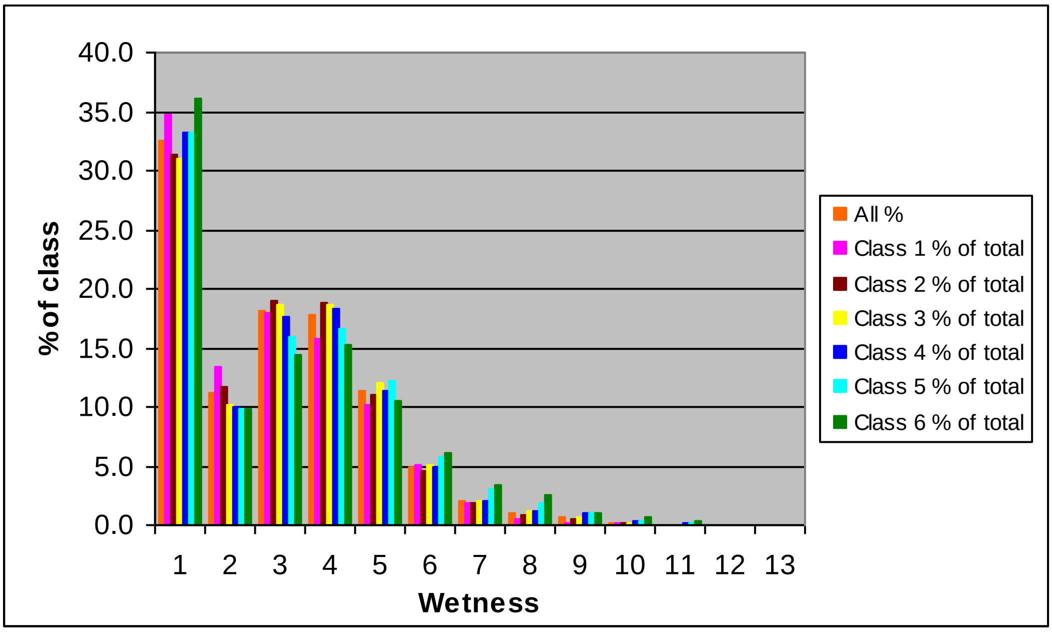


Figure 6.31 Percentage of NDVI pixels falling in each wetness category in Juan Contreras badlands

It can be seen that classes 5 and 6 are associated with higher wetness values and classes 1 and 2 are associated with lower wetness values. Classes 5 and 6 are often associated with the channel bottom in this subset indicating that they are in channels which have large areas feeding them. Classes 1 and 2 are found on the tops and sides of slopes where there is a large badland area, and thus have smaller catchments. Classes 4 and 5 are widely distributed across this subset.

Wetness value	NDVI Class					
	Class 1	Class 2	Class 3	Class 4	Class 5	Class 6
1	6.8	-3.6	-4.7	2.1	2.3	11.1
2	19.5	5.1	-8.7	-10.4	-11.6	-12.2
3	-1.0	5.5	3.1	-2.4	-12.1	-20.7
4	-11.1	5.5	5.0	2.4	-6.6	-14.1
5	-9.9	-2.3	7.3	1.3	8.0	-7.0
6	3.4	-9.8	2.6	-3.0	13.9	22.3
7	-8.8	-12.4	-1.0	-5.1	48.0	56.7
8	-46.9	-22.2	11.7	14.3	69.0	126.4
9 to 13	-60.0	-12.7	-2.4	45.0	57.4	113.6

Table 6.24 Percentage deviation from expected (o-e/e*100) values for NDVI by wetness pixels in Juan Contreras badlands

6.6.5.6 NDVI and wetness index in the Sorbas subset

Figure 6.32 shows the percent of each class in each wetness category in the Sorbas subset. Table 6.25 shows the percentage difference between the observed and expected wetness values for this subset.

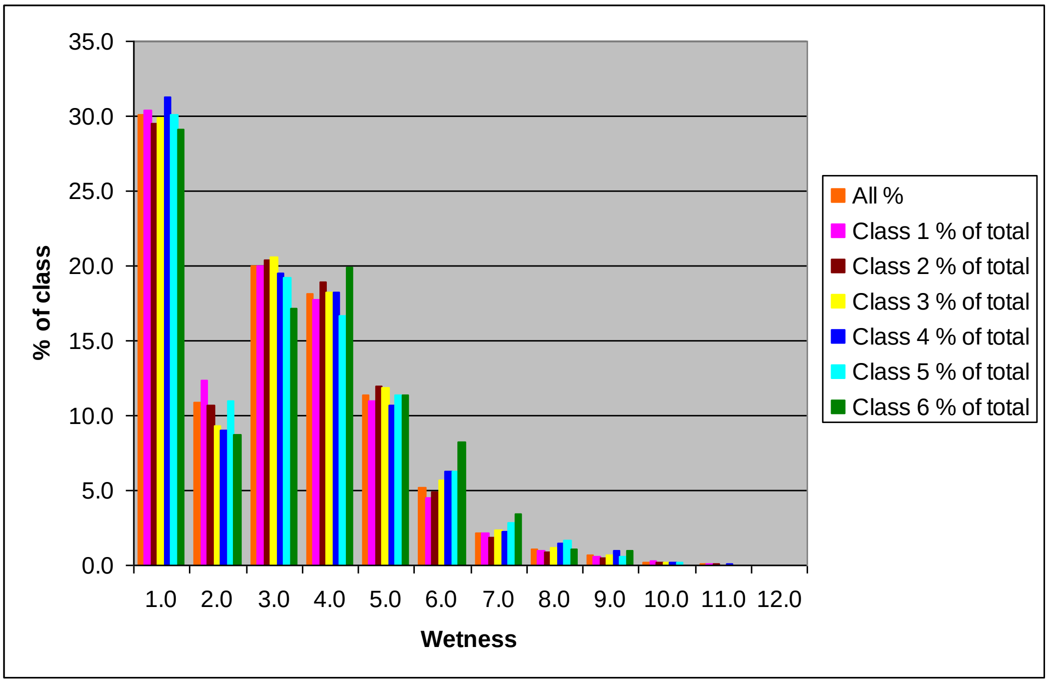


Figure 6.32 Percentage of NDVI pixels by class falling in each wetness category in the Sorbas subset

Classes 1, 2 and 3 are positively associated with high wetness values indicating that these classes are found in areas such as channel bottoms. Classes 4 and 5 are negatively associated with high wetness values but are not very strongly positively associated with low wetness values. Classes 4 and 5 are most often found on hilltops and hillsides in this subset and the wetness values support this observation. Class 6 is strongly positively associated with high wetness values which indicates that it can be found in areas at the base of long slopes. There appears to be either very dense or sparse cover in the channel bottoms in this subset which goes some way to explaining the NDVI class and wetness distribution of classes 1, 2 and 6.

Wetness value	NDVI Class					
	Class 1	Class 2	Class 3	Class 4	Class 5	Class 6
1	-7.6	-7.2	-9.9	-5.5	4.9	7.5
2	-28.1	-30.0	8.6	4.3	3.2	-9.7
3	-12.6	0.9	6.0	2.1	-0.2	-8.5
4	3.5	6.7	2.5	6.4	-2.7	-10.8
5	18.7	5.8	-0.3	4.3	-1.6	-10.8
6	40.4	22.9	5.3	-0.5	-6.6	3.1
7	72.4	13.2	12.6	-2.7	-13.6	31.5
8	28.8	73.0	11.5	-14.9	-25.3	88.5
9 to 13	25.6	82.2	13.8	-26.8	-22.3	96.6

Table 6.25 Percentage deviation from expected (o-e/e*100) values for NDVI by in the Sorbas subset

6.6.6 NDVI and wetness summary

Chi Square tests were carried out on all the wetness values for all classes in all subsets. All Chi Square results were found to be significant at the 0.01 level The Chi Square values for all wetness index categories in all subsets have been plotted on a single graph. This shows the classes which have higher Chi Square values and so are more associated with wetness values (Figure 6.33). Comparing the catchment level subsets it can be seen that the Infierno catchment NDVI class distribution has a higher association with wetness for most classes than the Mocatán catchment. In particular class 6 has a very high association with wetness compared to the other five classes in the Infierno catchment. Class 6 also has the highest association with wetness in the Mocatán catchment.

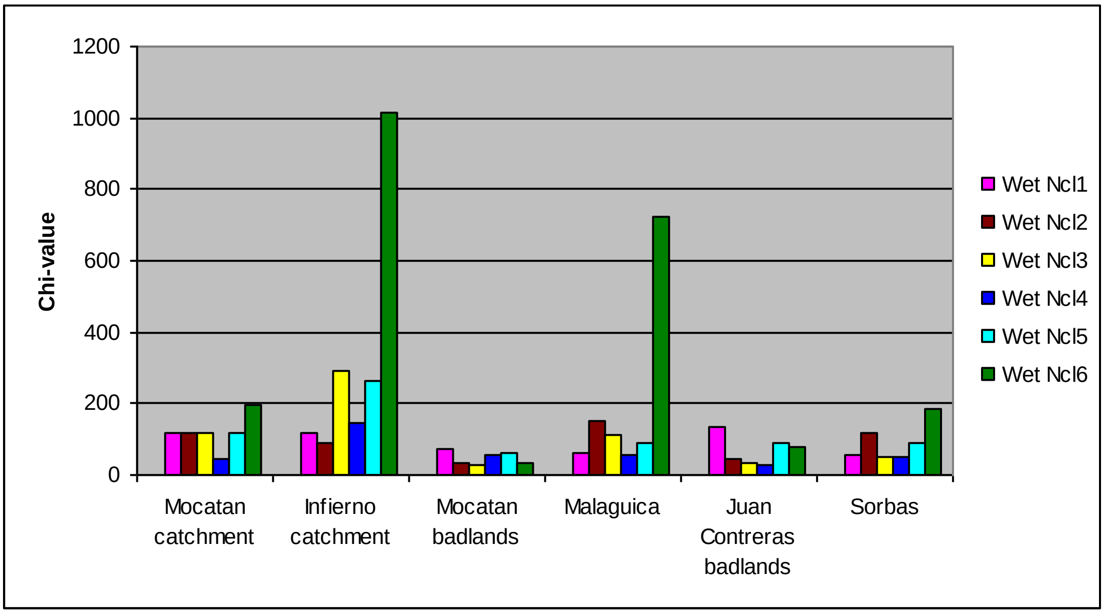


Figure 6.33 Bar graph showing wetness Chi Square values for each class in all subsets

In the four sub-catchment level subsets of the study area, wetness is an important environmental variable for class 6 in Malaguica and to a lesser extent in the Sorbas subset. The Mocatán badlands appear to have very little association with wetness value for any of the classes. In the Juan Contreras badlands class 1 has a higher association with wetness than in the other five subsets, where class 1 is positively associated with low wetness values and strongly negatively associated with high wetness values.

6.6.7 Comparison of aspect, slope and wetness data with NDVI class

Figure 6.34 shows all variables for all subsets plotted on the same graph. The environmental variable which has the highest Chi Square value is the variable which is the most strongly associated with the distribution of the NDVI classes. It is then possible to distinguish which variables have the most association with particular classes in all the subsets.

In the Mocatán catchment it is quite obvious that cover distribution for all classes is very strongly associated with aspect when compared to the slope and wetness Chi Square values. Classes 1 and 5 are particularly strongly associated with aspect, class 5, dense vegetation being found mainly on north facing slopes and class 1, sparse vegetation, being found mainly on south facing slopes. Class 3 is the most weakly associated with aspect although the Chi Square value is still higher than any slope and wetness index values. Slope and wetness seem to have little association with cover distribution for any of the classes in this subset.

The Infierno catchment has extremely high Chi Square aspect values for classes 1, 2 and 5 and much smaller values for 3, 4 and 6. Class 1 also has quite a high Chi Square value for slope. Classes 1 and 2 are strongly associated with south facing slopes and class 5 is associated with north facing slopes. Of the three environmental variables, slope, aspect, wetness values, class 6 in the Infierno catchment, has the highest associations with wetness and aspect. When this is compared to all the other classes, it indicates that class 6 is much more strongly associated with wetness than any of the other classes and much less strongly associated with aspect and slope than the other five classes. This would appear to indicate that wetness has an effect on the distribution of class 6, and hence, that very dense cover in the Infierno catchment is found where water collects.

The Mocatán badlands have high Chi Square values for classes 1 and 5 and aspect, although these are only half as high as the equivalent values for the same classes in the Mocatán catchment as a whole, indicating that aspect is not as important an environmental variable in this subset. Class 1 has quite a high Chi Square values for slope. There are low wetness values for all classes, indicating that this variable is less important in this subset. It would seem that an environmental variable which has not been investigated may be important in this subset, for example soil chemistry, geology or erosion.

The Malaguica subset has very high Chi Square aspect values for classes 1, 2 and 5 indicating that these classes may be aspect dependent in this subset. Classes 1 and 2 are found facing in southerly directions and class 5 in a north-easterly direction. Class 4 in this subset is also found to have a high aspect association where it can be found generally facing in a north-westerly direction. Classes 3 and 6 are much less aspect associated than the other four classes. Class 3 has almost as much association

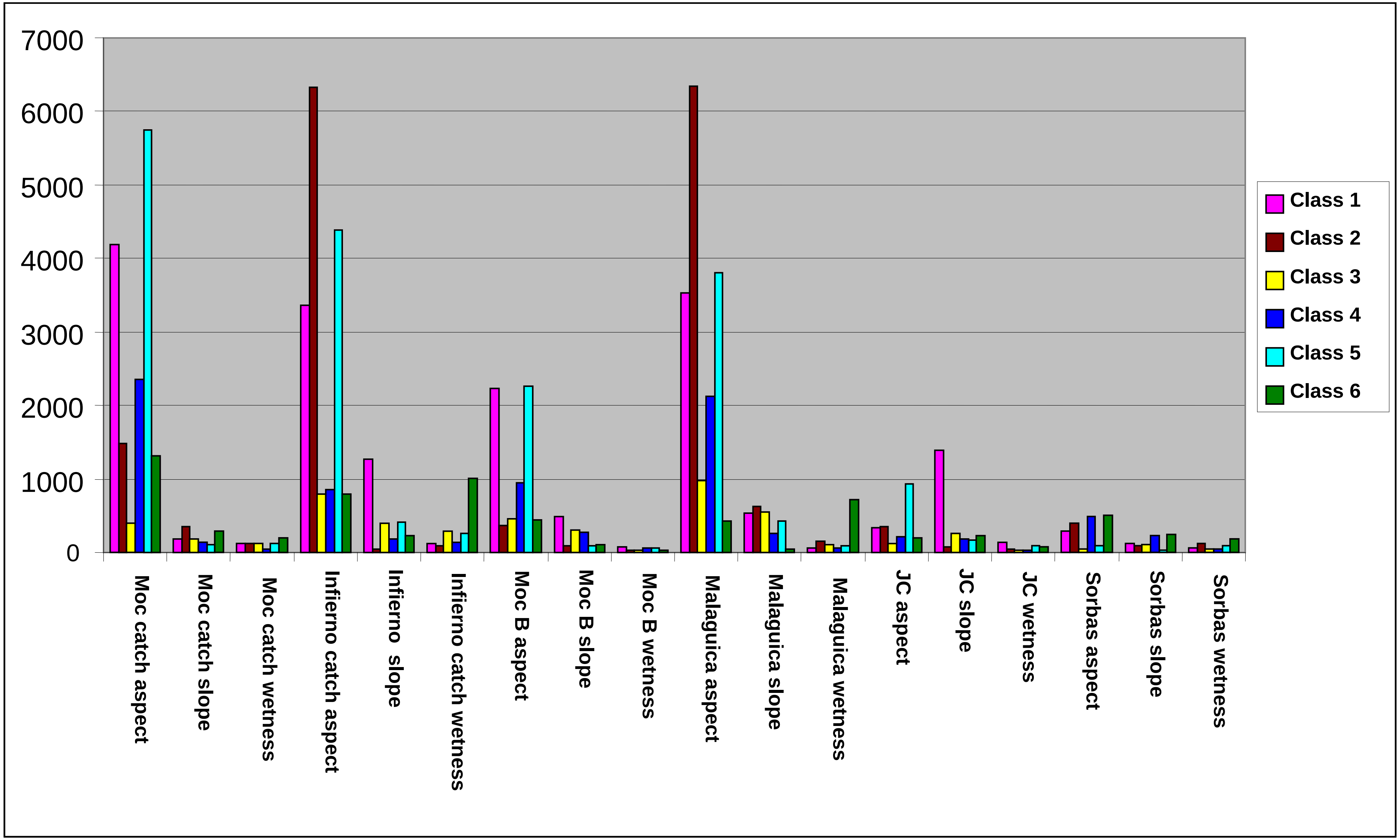


Figure 6.34 All class Chi Square values for each environmental variable in each subset to allow comparison between values

with slope as with aspect. Class 6 in this subset is more associated with wetness value than any of the other environmental variables, again indicating that class 6 is more likely to be found in areas where water collects.

The Juan Contreras badlands subset has generally low Chi Square values for all three environmental variables. There are two exceptions to this; class 5 has a medium level association with aspect where it is predominantly found facing in a north-easterly direction and class 1 has an association with slope occuring mainly on steep slopes. The class 1 cover found on steep slopes relates to the large expanse of badlands in this subset.

The Sorbas subset has low Chi square values for all classes with all variables. Aspect is the most associated with cover type, but the differences between the values for aspect, slope and wetness scores are very small. It should however be noted that in this subset, class 6 is more associated with aspect than either slope or wetness.

Finally, to sum up the gross differences between aspect, slope and wetness values, the Chi Square values for each subset for each environmental variable were added together to demonstrate how much each variable contributed to the distribution of NDVI classes in the study area. These figures are shown as a graph in Figure 6.35.

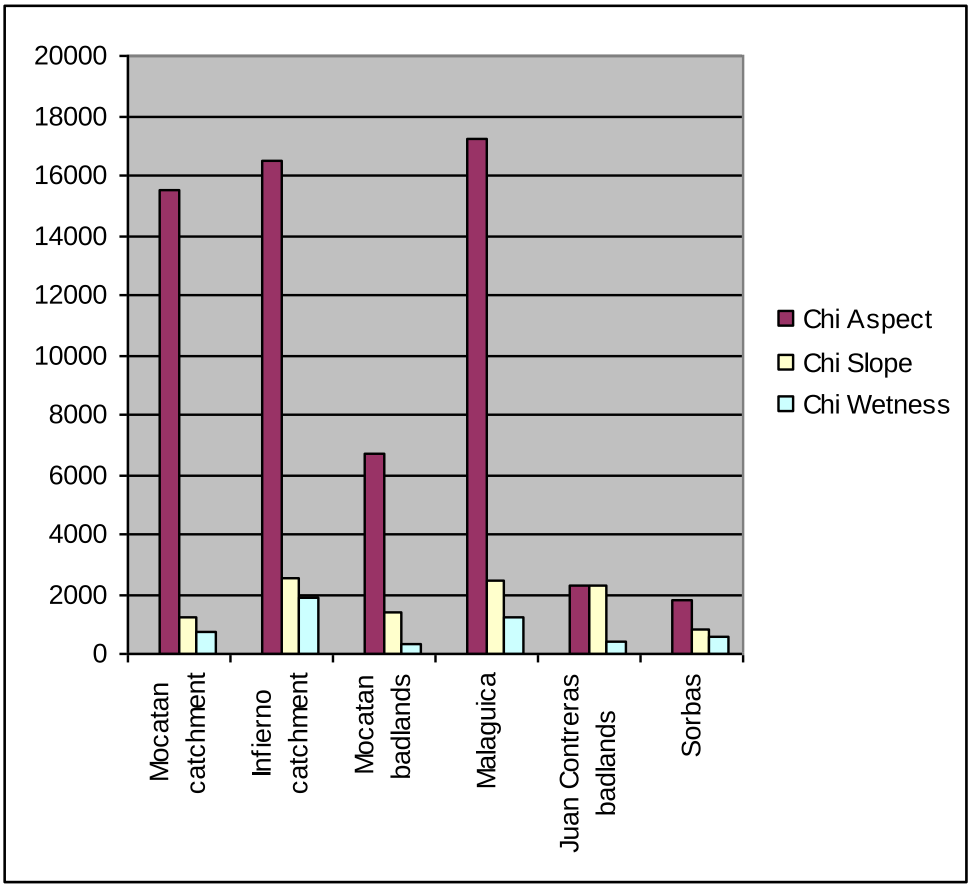


Figure 6.35 Total Chi Square values for aspect, slope and wetness by subset

All the Chi Square values for each subset were added together and then used to produce a percentage value for each environmental variable in order to indicate how much of the variation in cover is associated with each environmental variable (Table 6.26). The Mocatán catchment has the greatest difference between the three variables. Aspect is associated with a very large amount of the variation in cover patterns in the Mocatán catchment. NDVI class in the Juan Contreras badlands subset is most associated with aspect, but the differences are a lot smaller than in the other subsets as slope is associated with NDVI class to the same extent.

Section	Aspect %	Slope %	Wetness %
Mocatán catchment	88.8	7.1	4.1
Infierno catchment	78.7	12.1	9.1
Mocatán badlands	80.4	16.2	3.5
Malaguica	82.6	11.7	5.7
Juan Contreras badlands	46.0	45.7	8.2
Sorbas	57.3	25.4	17.4

Table 6.26 Showing percentage of the total Chi Square values each environmental variable comprises for each catchment

In all subsets aspect is the most important environmental variable related to variation in NDVI class. However, the gross totals belie the fact that there is variation in association with these environmental variables between classes. The most important being that in three of the six subsets, class 6 is associated more with high wetness values than aspect and class 1 is highly associated with slope in the Infierno catchment and Juan Contreras badlands. Classes 1 and 5 are extremely highly associated with aspect in the Mocatán catchment, the Infierno catchment, Mocatán badlands and Malaguica and are found at opposite sides of the compass, class 1 taking the southerly side and class 5 taking the northerly side.

In summary all the Chi Square values are significant for all environmental variables in all classes. This indicates that these three variables (slope, aspect and wetness) are important in the explanation of the distribution of cover throughout the study area. However, aspect is the most important variable investigated for distribution of most of the classes in most of the catchments.

6.7 Summary

In summary, the four clustered NDVI images were investigated to see which image demonstrated the best relationship with the ground cover for use with other environmental variables for investigation of the study area. The six class image was chosen as it provided the best division of landcover types. The six class NDVI image was compared to cover data from training areas surveyed in 1997 and 1998 and a description of each class was obtained using this information. The classes were then appraised using smaller quadrats collected in 2000. There were some differences in cover totals between the two sets of cover data, and these differences can be attributed to precipitation amounts and surveying technique. It was decided to continue using the descriptions of the six classes obtained from the 1997 and 1998 data even though there were slight discrepancies with the 2000 cover data totals for classes 2 and 3. Therefore the clustered NDVI image can be used as a map of ground cover, and to some extent type of plant community. Having obtained a map of cover, it was then possible to compare cover types with other environmental variables acquired from analysis of the DEM using GIS functions in ERDAS Imagine. Aspect, slope and wetness for each pixel in each class were compared. The results of the analysis demonstrated that aspect is a key variable, being associated very strongly with the distribution of cover classes across the study area. However, both slope and wetness are also strongly associated with distribution of some cover classes in some parts of the study area. In Chapter 7, the NDVI cover map of the study area is subjected to some quantitative landscape ecological tests to identify how the classes relate to themselves and each other on a catchment and sub-catchment level.

7 LANDSCAPE ECOLOGICAL ANALYSIS OF THE CLUSTERED NDVI IMAGE

7.1 Introduction

Landscape ecology is concerned with the ecological effects of the spatial and temporal distribution of different structural components within a landscape, the structural components can be effectively represented by landcover units. Definitions of landscape ecology vary between authors. Naveh's (1989) definition of landscape ecology is a discipline which includes natural phenomena (for example geomorphology and ecology) and also includes social and economic aspects of the human environment. Zonnveld (1979) defines landscape ecology as an aspect of geography which sees the land as an holistic entity made up of differing parts, all influencing each other. Forman (1995 p45) simply describes landscape ecology as " the ecology of landscapes". Landscape ecology crosses the boundaries of disciplines and has the effect of filling some of the gaps between the various disciplines involved (Naveh, 1989). Landscape ecology differs from ecology in that whereas ecology has always sought spatial homogeneity for ease of analysis, landscape ecology sees spatial heterogeneity as a central causal factor in ecological systems (Pickett and Cadenasso, 1995).

Turner's (1989) definition of landscape ecology focuses on the broad spatial scales and ecological effects of the spatial pattering of ecosystems. This definition of landscape ecology includes development and dynamics of spatial heterogeneity and interactions and exchanges across heterogeneous landscapes. The influences of spatial heterogeneity are particularly important for the distribution of biotic and abiotic processes. Forman and Godron (1986) define landscape ecology as the study of the structure, function and change of a heterogeneous land area comprising of interacting ecosystem types. Structure is the spatial relationships amongst the elements present in the landscape; the distribution of energy, materials and species in relation to the shapes, sizes, numbers, kinds and configurations of the ecosystem. Function comprises the interactions amongst the spatial elements – the flows of energy, material and species between the components of the landscape. Change is the alteration in the structure and function of the ecological mosaic over time (Forman and Godron, 1986). To sum up the basis of landscape ecology; there is a strong correlation between ecological pattern and ecological process (Gustafson, 1998) and by quantifying the landscape pattern, the processes at work in the landscape can be inferred.

The investigation of the study area comprising the Barrancos del Infierno and del Mocatán has been carried out in a way which reflects Forman and Godrons' (1981 and 1986) and Turner's (1989) definitions of landscape ecology. The landscape has been examined to seek to understand the reasons behind its spatial heterogeneity, and the production of the various images for examination has been carried out to attempt to explain the structure and function of the landscape and the way it has changed over time. By quantifying the pattern in the landscape of the study area it should be possible to infer the processes acting on the elements of this landscape.

This chapter discusses the elements of landscape ecology and how they can be quantified using FRAGSTATS a freeware landscape pattern quantification program. It will then illustrate how FRAGSTATS and other techniques were used to acquire landscape metrics for the six clustered NDVI subsets of the study area and report the results for these metrics and their interpretation.

7.2 Elements of landscape ecology

The landscape can be divided up into "Landscape elements" or ecotopes of homogeneous composition. An ecotope is the smallest possible piece of land that can be described as an holistic unit – i.e. consisting of a homogenous land cover. Landscape elements can very from $10m^2$ to $1km^2$ in area and should be big enough to be visible on aerial photographs (Forman and Godron, 1986). These components of a landscape are the building blocks of landscape ecology. There are three main landscape components; patches, corridors and the matrix which together form a landscape mosaic (Forman, 1995; Farina, 1998). Boundaries (also known as 'ecotones' or 'transitional areas' (Kent *et al,* 1997)) between landscape elements play a very important role in the transfer of matter and energy and can act as barriers to movement of species (Forman and Godron, 1986).

7.3 Patches, corridors and the matrix

Patches are non-linear landcover areas differing in appearance from their surroundings. Patch boundaries are distinguished by discontinuities in environmental character (McGarigal and Marks, 1995) They vary widely in their shape, size, type, heterogeneity and boundary characteristics and are most often contained within a matrix (Forman and Godron, 1986). Corridors are narrow strips of land which differ from the matrix on either side. They are important in the landscape as a means of transfer of energy and material and species across the matrix between patches of similar cover. The matrix is the most extensive and connected of the landscape elements and has a controlling role in the flow of energy and materials in the landscape (Forman and Godron, 1986). The most common use of landscape ecology is to elucidate the interactions of these landscape elements which make up the landscape mosaic (Pickett and Cadenasso, 1995).

7.3.1 The issue of scale

Patches occur at all scales from micro-scale to macro-scale. Landscape ecology is interested in patches which occur in landscapes, a landscape being defined by Forman and Godron (1986) as a "few kilometres in diameter". Within this landscape, patches can range from a few metres in diameter to hundreds or thousands of metres in diameter. However, within each patch which appears homogenous at one resolution, at a finer resolution it will be possible to identify finer patches. This nesting of scales is important for an organism-centred landscape ecology, particularly for studies with fauna which have different scales of range. What is a patch for one animal or a plant's seed distribution would become a landscape for another with a smaller range (McGarigal and Marks, 1995).

The study area landscape covers 1.6x2km, and is therefore what Forman and Godron would describe as a small landscape. It is acknowledged that the boundaries of the study area do not follow a natural boundary between one type of landscape and another. This is due to the factors of time constraints upon sampling, the availability of information and ease of access to field sites. Within the study area, subsets of similar landscape cover pattern in the clustered NDVI image were delineated (see chapter six for subset definitions). At a coarse resolution these subsets would be seen as patches (e.g. from an AVHRR satellite with a resolution of $1km^2$). However at the resolutions available using the ATM data and aerial photography, patches within these mini-landscapes can be distinguished.

7.3.2 Patch types

Patch characteristics are important for determining the flow of energy, organisms and abiotic factors throughout the landscape. Forman and Godron (1981 and 1986) identify a number of distinctive types of patch in the landscape, each of which has a different origin. The different origins determine how long the patch stays distinct from the rest of the landscape - some are long lived, others have a brief lifespan. Understanding the nature of the patches in the field area allows an understanding of the way the landscape is working. Descriptions of each patch type with examples taken from the field area are given below.

7.3.2.1 Disturbance patches

Disturbance patches appear when a small area of the matrix is disturbed. These patches indicate that environmental conditions have changed in the landscape from a stable state to a disturbed state, which encourages a change in the ecosystem. Initially after a disturbance, population sizes of many species change rapidly, many are damaged directly by the disturbance. Some species may even become locally extinct. The species left will expand into the bare areas, and immigration of species originally absent from the area will take place as they colonise the newly opened patch. The patch is usually short lived, and as species colonise it, the patch will become indistinguishable from the surrounding matrix (Forman and Godron, 1981 and 1986).

There is an exception to the short-lived disturbance patch in the form of a chronic disturbance patch which persists for a long time (Forman and Godron, 1996). A chronic disturbance patch occurs in an area where part of the matrix is disturbed, moves back towards equilibrium and is then disturbed again. It is suggested that some of the patches of bare ground in both the Mocatán catchment and the Infierno catchment would come under the heading of chronic disturbance patch. It is probable that some of the bare areas are being constantly disturbed by erosion during wet periods which indicates that areas which should be recolonised by species from the surrounding matrix are unlikely to be colonised as, during the next period of wet weather, more erosion takes place. After a while, this process is likely to lead to a state where the bare patch is no longer a disturbance patch, but could be reclassified as an environmental resource patch because it will no be longer able to support the type of flora that it originally supported due to loss of soil.

7.3.2.2 Environmental resource patches

Environmental resource patches occur where there is an underlying difference in the environment compared to the surrounding area (Forman and Godron, 1981 and 1986). These patches are permanent in the environment (over a meso scale time period) and have relatively stable boundaries (Forman, 1995). Examples of environmental resource patches can include springs at the surface, geology or soil differences. All these will cause differences in vegetation within the patch compared to the surrounding vegetation. A good example of an environmental resource patch in the study areas would be a patch of very dense vegetation in the Barranco de los Contreras which surrounds a section of the barranco containing a permanent spring (Fig 7.1 at 1). As discussed in section 7.3.2.1, within the study area, patches that have been disturbed many times by erosion will become environmental resource patches as they have their soil removed. This process creates a resource patch (or in this case, a lack of resource patch!) as the original plant species are not able to re-establish due to the impoverished soil.

Figure 7.1 Aerial photograph illustrating points made in the text

7.3.2.3 Remnant patches

Remnant patches are the opposite of disturbance patches, i.e. a small undisturbed area in the landscape surrounded by widespread disturbance. Examples of remnant patches include a non-burned area after a fire, or an island left in the middle of a flooded valley. Immediately after the disturbance, there seems to be a high rate of extinction from the remnant patch, which will gradually decline to zero after a period of time. This is known as the relaxation period (Forman and Godron, 1981) As with the disturbance patches, if the surrounding disturbance is temporary, succession will continue until the area becomes homogeneous again. However it has been found that due to the immediate extinction and the disturbance to the surrounding matrix, the remnant patch, when finally rejoined with the matrix is a species-poor copy of the original ecosystem (Forman and Godron, 1986). If the disturbance is chronic then the patch will stay as a patch (Forman and Godron, 1986). This latter situation appears to describe areas in the Mocatán catchment. In the Mocatán catchment, patches of dense shrubby vegetation exist on ridge tops and sides. Many of these patches are cut off from other patches of similar vegetation by eroded areas of bare or mostly bare cover. As the disturbance in the Mocatán catchment is chronic, it seems unlikely that the remnant patches will join up again. From field observation, it has been seen that the densest areas of vegetation on Cerro de Juan Contreras have higher numbers of large woody shrubs than the areas of dense vegetation that are cut off. For instance *Pistacia lentiscus* and *Olea europa* have been observed on the sides of Cerro de Juan Contreras, whereas these species have not been observed in the smaller, cut off areas of dense vegetation indicating that local extinctions of woody shrubs have been taking place in the isolated areas of dense vegetation, and the isolation of these patches stops the woody species recolonising. These observations are supported by findings of Alexander *et al* (1999) where species diversity appears to be related to patch size in the Mocatán catchment.

7.3.2.4 Introduced patches

Introduced patches occur when humans introduce organisms into the original environment. These can include agricultural fields, parks, plantations and anywhere that an organism not belonging to the natural matrix has been introduced. Introduced patches also include inanimate patches such as houses and urban areas, roads, railways and canals. It is people that are the dominant force behind these patches, and the patches will remain established as long as they are maintained by humans (Forman and Godron, 1986). Examples include the extensive agricultural terracing throughout the field area. The maintained agricultural terracing is an example of an introduced patch as it often contain crops of, for example, cereals, which would not be found in this environment in the monoculture concentrations in which they are planted. However, when the agricultural terraces are abandoned, the natural environment reclaims the terrace fields through reshaping by erosion and recolonisation by plants from the surrounding hillslopes. These new patches either return to the matrix or become regenerated patches.

7.3.2.5 Regenerated patches

A regenerated patch resembles a remnant patch, but has a different genesis. The establishment of regeneration patches often takes place in areas which were previously undergoing chronic disturbance, but are now free of disturbance (Forman and Godron, 1986). The regenerated patch will look like a remnant patch as it will still be adjacent to some disturbance, however it will be accumulating species rather than losing them due to disturbance. Some areas of the Infierno catchment are likely to come under this heading as post-agricultural terrace abandonment erosion reaches an equilibrium allowing regeneration of plant cover:

7.3.3 Corridors

Corridors are narrow strips of land which differ from the matrix on either side. Although corridors may be isolated strips, they are more usually attached to a patch of somewhat similar vegetation. There are four different types of corridor.

a. Line corridors such as paths, railways, hedgerows. These are composed only of edge species because they are too narrow to be able to support interior species.

b. Strip corridors, which are wide enough to contain interior species, and seem to be a form of very elongated patch. These are useful as migratory corridors for interior species.

c. Stream corridors, bordering watercourses.

d. Corridor networks formed by intersecting corridors, e.g. a series of hedgerows bounding fields. (Forman and Godron, 1981)

Corridors tend to originate in the same way as patches, with human interference in the landscape being one of the main instigators of corridor formation. Corridors can act as a pool of interior species, replenishing connected patches that have lost species. There are a few examples of corridor patches in the study area, the main ones being stream channels. From study of the aerial photograph it is possible to identify the stream channels as linear features which are heavily vegetated in the Infierno catchment (Fig 7.1 at 2). The stream corridors appear to be a focus for erosion in the Mocatán catchment and for re-colonisation by vegetation in the Infierno catchment. One of the other most visible linear features is the gypsum covered track which runs along the centre of the image (Fig 7.1 at 3). However, the gypsum track supports very little vegetation so is discounted as a feature which could allow ease of travel for species.

7.3.4 The matrix

The matrix is usually the most extensive landscape element which appears to hold the patches and corridors inside it (Forman and Godron, 1986). The matrix, being the dominant landscape element tends to control the flows of energy, materials and species though the landscape. Forman and Godron (1986) give three criteria for distinguishing the matrix in a landscape: relative area, connectivity and control over landscape dynamics.

7.3.4.1 Relative area

When one class of landscape cover is much more extensive than others, it is usually appropriate to designate this cover type as the matrix. Species that are prevalent in that landcover type will therefore be prevalent in the landscape. The most extensive cover is likely to control the flows of energy and material throughout a landscape (Forman and Godron, 1986). If the area of a particular landcover type exceeds the **total** area of all other cover types in the landscape then this is designated the matrix. The relative area of a particular landcover type is usually easy to discern using remote sensing or even just estimating by eye using aerial photography. However, often the area of one landcover type does not exceed the total area of the other landcover types. In this case other criteria have to be applied to identify the matrix.

7.3.4.2 Connectivity

Connectivity is defined as being "the binding that surrounds and cements the independent elements" of a landscape (Forman and Godron, 1996 p.162). Connectivity is defined by Forman (1995) as the inverse of the proportion of linkages needed to have a fully connected system. A space is completely connected if it is not divided into two open wholes (i.e. is not crossed by a boundary which bisects the whole area of interest). Generally, a landscape cover type will not completely encircle patches of other landscape cover types. However, the matrix can be defined as that element which is more connected than other elements present and when combined with the highest proportion of cover then this element can be defined as the matrix (Forman and Godron, 1986). Connectivity is a structural attribute of the landscape and can therefore be mapped (Farina, 1998) In some cases a matrix element will not be obvious in the landscape - this can often be a function of the scale at which the landscape is being investigated (McGarigal and Marks, 1995).

7.3.4.3 Control over dynamics

Control over dynamics is what the first two criteria of the matrix are indirectly measuring (Forman 1995). Assessing control over dynamics involves identifying that landscape element which is the 'engine' that drives change in the landscape, for instance, acting as a species store. The matrix exerts a major control over landscape dynamics by giving rise to future landscapes. This criterion cannot be measured directly, but has to be estimated using other sources of information (Forman and Godron, 1986). As control over dynamics is so difficult to determine, this test should only be used for matrix identification if neither of the first two tests have clearly determined the matrix.

7.4 FRAGSTATS and patch metrics

Patch characteristics and dynamics will be described in the following section and examples of the FRAGSTATS metrics that can be used to describe each attribute will be cited. FRAGSTATS is an example of software that has been produced to provide a quantitative description of landscape structure. In this study FRAGSTATS was used to investigate the clustered raster NDVI image. FRAGSTATS can also be used with vector data, but fewer metrics can be calculated. FRAGSTATS outputs a series of metrics at the individual patch, class within the landscape and whole landscape levels. Some of the metrics can only be used at one level (e.g. only at patch or only at landscape level), and other metrics can be used on all three levels. Metrics that can be produced using Fragstats are discussed below together with an explanation of their use. Mathematical definitions of the metrics can be found in McGarigal and Marks (1995). FRAGSTATS metrics discussed are highlighted in bold in the following text. As the interest in the study area is at the class and landscape level, FRAGSTATS metrics that apply purely at the individual patch level are not discussed. Metrics for individual patches would be more useful in a landscape where only a few patches are being investigated (i.e. a landscape which is composed of a few, large patches rather than the many, tiny patches found in the study area).

FRAGSTATS was selected for use here primarily because it contains a number of commonly used landscape metrics. Using FRAGSTATS instead of using landscape metric equations individually saved time and effort and also reduced the possibility of user error due to unfamiliarity with the equations needed in the quantification process. It is acknowledged that there are other indices available for landscape quantification not included in Fragstats, but FRAGSTATS appears to be becoming a standard package for landscape quantification and was deemed sufficient for the purposes of this analysis.

7.4.1 Patch size and area

Patch size has a bearing on the number and type of species that a patch can support. Forman (1995) discusses the ecological values of a single large patch compared to several small patches of the same species assemblage with the same total area. In general large patches provide major benefits in the environment including sustaining core habitat, being a source of species to the matrix, and buffers against local extinction during environmental change. Small patches are also beneficial to the environment, but only as a supplement to large patches, not on their own. These add-on benefits include high species density and high populations of edge species, matrix heterogeneity which decreases erosion and habitat stepping stones for recolonisation after local extinction of interior species. Forman (1995 p48) comments that "A landscape without large patches is eviscerated, picked to the bone. A landscape with only large patches misses few values". Larger patches contain more energy and nutrients than smaller patches and are more stable and less prone to change (Forman and Godron, 1986). The factors which allow large patches to support larger numbers of species than small patches are somewhat similar to the ideas of island biogeography (McArthur and Wilson 1967) where a small island will be able to support less species diversity than a large island. However, the comparison can only be drawn so far, as an island has fewer opportunities for recolonisation after extinctions than a patch. For a terrestrial patch, rapid recolonisation is much easier than for an island and isolation is minimised (Forman and Godron, 1986). Alexander *et al* (1999) demonstrated that species diversity rose as patch size increased in the Mocatán catchment indicating that patch size does have a bearing on species numbers in the field area.

7.4.1.1 Area metrics

Within FRAGSTATS, area metrics quantify landscape composition, not configuration. Composition refers to the features associated with the presence and amount of each class/patch type within the landscape, as opposed to the physical distribution/spatial character of patches in the landscape; which is configuration. Patch area is the basis for many of the indices included in Fragstats. Patch area also has ecological value (as described above) and it has been determined that abundance of species is often linked to patch size (Robbins *et al*, 1989). The metric, **class area,** gives the area of each class in the landscape and **total area** is simply a measure of the size of the landscape being investigated and is used to calculate the percentage of landscape for each class index. **Largest patch index** is calculated for both class and landscape. For a class it is the area of the largest patch in that class is calculated as a percentage of that class. The largest patch in a landscape is calculated as the percentage of the total landscape area as comprised by the largest patch.

7.4.1.2 Patch density, size and variability metrics

These metrics are best considered as representing landscape configuration, although they are not spatially explicit. **Number of patches** is calculated for class and landscape. Number of patches of a particular habitat type may indicate fragmentation of that class within a landscape. It is generally most useful for calculating other metrics as by itself it conveys little information about the distribution, area or density of patches. **Patch density** expresses the number of patches per unit area which allows comparisons between classes within the same landscape and can be used to indicate fragmentation of a class within a landscape. **Mean patch size** is an important index which can be used to indicate fragmentation of a class as a smaller mean patch size is an indicator of habitat fragmentation. **Patch size standard deviation** and **patch size coefficient of variation** are both second order statistics which convey useful information that is not available from the first order statistics. These two metrics indicate variation in patch sizes within each class and across the whole landscape. Patch size standard deviation measures absolute variation around the mean, but this is difficult to interpret without doing so in conjunction with mean patch size. Patch size coefficient of variation measures relative variability around the mean (i.e. as percentage of the mean) and therefore takes the mean patch size into providing a more useful statistic.

7.4.2 Patch dynamics and boundary shape

Patch shape is an important control on process rates and dynamics within the landscape. Patch shape regulates the flows of energy and materials within and between patches (Forman and Godron, 1986). Ecological functions of patch shapes can be grouped into four attributes of shape: a) elongation, b) convolution c) interior and d) perimeter (Forman, 1995). A patch with a highly irregular shape will have more edge for interaction with the rest of the landscape than a regular (circular) patch where the ratio of edge to interior is much lower (Forman and Godron, 1986). Elongated patches (i.e. where the edge to interior ratio is greater than that of a round patch see section 7.4.3) are less effective at conserving internal resources than round patches (Forman, 1995). Compact forms are more effective at conserving resources. A patch with a low edge to interior ratio is more likely to have ‘core area’ than a patch with high edge to interior ratio (Farina, 1998).

FRAGSTATS shape metrics quantify the landscape configuration by complexity of patch shape. Patch shape metrics are related to edge metrics, discussed in section 7.4.3, as a convoluted patch with the same area as a circular patch will have a much longer edge than the circular patch. The **landscape shape index** measures the perimeter to area ratio for the landscape as a whole. It quantifies the amount of edge present in the landscape relative to what would be present in landscape with the same area, but a simple geometric shape. This is the same as Patton’s (1975) habitat diversity index.

However, this metric is not recommended for use when a landscape does not have meaningful boundaries (e.g. the landscape has been subset out of a similar landscape cutting patches in half). A landscape shape index can be derived as the **Mean shape index** which simply uses the Patton diversity score of each patch and then averages it either for class or landscape. **Area weighted mean shape index** weights patches according to their size so that large patches are weighted more heavily than small patches in calculating the mean.

The shape indices above have some limitations. In a raster landscape, perimeter length will be increased by the stair-stepped effect of the pixels. The perimeter to shape ratio is quite insensitive to differences in patch form – patches of different form may have the same perimeter length and area thus giving the same index score. Shape indices are best regarded as measures of shape complexity.

7.4.2.1 Patch boundaries

The shape of the boundary between landscape elements is important. In cases where a landscape element is spreading, it will tend to have convex edges, whereas a shrinking element will have concave edges. This leads to a landscape pattern where patches can often be identified as either shrinking or growing, which is useful when studying vegetation change as it can be used as a snapshot in time to tell which landscape elements are under pressure. A growing patch will often have convex boundaries, a shrinking (or relict) patch, concave boundaries (Fig 7.2a and b) (Forman and Godron, 1986).

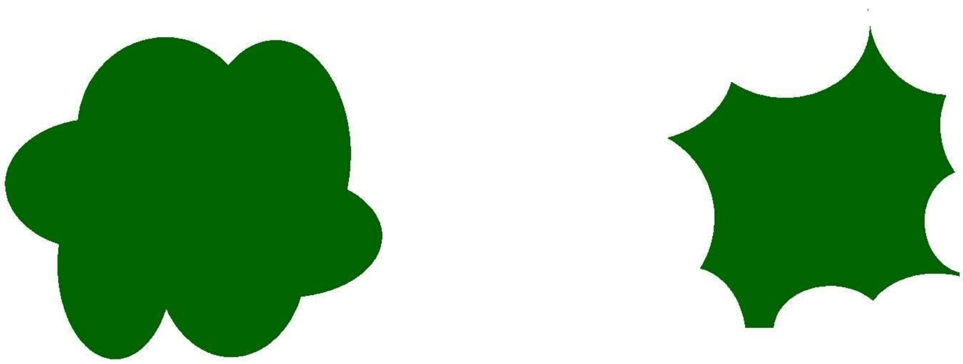


Figure 7.2 a) Convex spreading patch **b) Concave relict patch**

(after Forman and Godron, 1986)

There are a number of exceptions to this general rule of boundary shape, one of the most common is that of colonisation over time up a river valley where the colonising corridors of vegetation have definite concave boundaries (Fig 7.3). However, if the colonisation is allowed to proceed undisturbed, eventually the concave boundaries between the fingers of vegetation will become smoother over time.

The ‘fingers’ in the case of this sort of expanding patch are the result of a steep environmental gradient which eventually becomes less steep as colonisation progresses.

Patch boundaries are only meaningful when referenced to a particular scale (McGarigal and Marks, 1995). For instance, at a coarse resolution (e.g. 30m+ pixels size) the landcover in the study area would appear to have homogenous patches of cover which at a finer resolution (e.g. 5m pixel resolution) would be picked out as a heterogeneous cover. It is possible to see this difference in patch boundary recognition using the ATM data and the aerial photographs of the study area. The former is at 5m resolution and the latter at 50cm resolution. For example, areas of apparently homogenous landcover at 5m appear heterogeneous at 50cm.

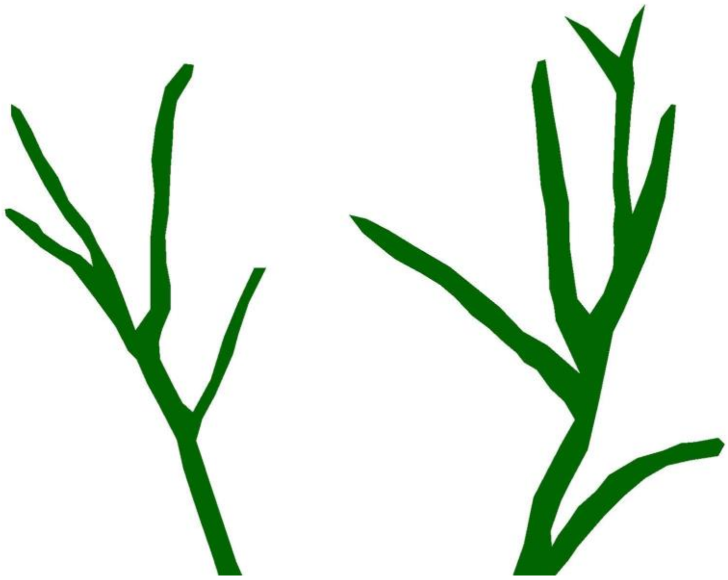


Figure 7.3 Spreading patch/corridor with concave boundaries (after Forman and Godron, 1986)

7.4.3 Edges, core area and interior species

Edge metrics represent the amount of edge in a landscape at the patch, class and landscape levels. Edge metrics represent landscape configuration, but again, as with patch metrics, are not spatially explicit. In landscape ecology, edge is important as it is related to many ecological phenomena. This is because it occurs at the boundary between patch and matrix, and it is here that transfers of energy, material and species take place. Much of the importance of spatial pattern is related to edge effects. The contrast between patch and neighbourhood influences many ecological processes, and these are particularly influenced by the degree of difference between a patch and its surrounding neighbourhood. A patch is usually thought to consist of core and edge, with the core being the interior of the patch where edge effects do not occur. **Total edge** is the absolute measure of total edge length of a particular patch type at class level or of all patch types at landscape level. **Edge density** is described as being a standardisation of the edges to a per unit area measure which allows comparisons between different classes in the same landscape or comparisons between different landscapes.

Core area is defined as the area within a patch beyond a specified edge distance or buffer width (McGarigal and Marks, 1995). This ‘specified edge distance’ is a loose definition depending on the type of plant communities, direction the patch faces and latitude of the landscape (Forman and

Godron, 1986). There appears to be no one quantifiable definition of edge. In most cases, edge is an area where the species composition is different and more diverse than the core.

Core areas have 'interior species' in the centre of the patch at a distance from the boundary. These core areas are more stable than the edges of the patches and provide habitats for slow growing plants or larger animals. However, core areas generally do not have as great a species density as the edges of a patch (Forman, 1995). The fragmented, heterogeneous nature of the environment in the study area seems to make it unlikely that there are very many patches which are large enough to have core areas. FRAGSTATS core area metrics are used to determine the behaviour of the areas in patches away from the core. This is particularly useful in studies which contain large patches or in areas where there is a distinct edge/patch difference. FRAGSTATS asks the user to input a figure for the width of the edge of the patches. Most of the time this is an arbitrary figure based on user knowledge of the area being studied and the patches within it. For the study undertaken, the patches are so small and convoluted in most cases that even with an edge of as little as 10m, there was no core left upon which to perform the calculation of core area metric.

7.4.4 Fragmentation of landscapes

Fragmentation is the process of a large habitat or landcover type being broken into smaller pieces (Forman, 1995). Fragmentation lowers connectivity of habitats and can cause the decline in species found in the fragmented area over and above the losses that would be predicted strictly on estimates of habitat loss (Schumaker, 1996). The smaller the fragmented blocks of habitat, the more population density of the whole habitat decreases and therefore extinction rates of species in the fragmented habitat are higher (Farina, 1997). The geographical isolation imposed on a habitat by fragmentation becomes a progressively more important factor in the ability of a landscape to recover as patches of the same type get more distant.

7.4.4.1 Nearest neighbour and mean proximity metrics

Nearest neighbour analysis in the FRAGSTATS program can be used as a measurement of fragmentation. Nearest neighbour is defined as the distance from a patch to the nearest neighbouring patch of the same class based on edge to edge distance. Nearest neighbour distance can influence a number of important ecological processes as population dynamics in a patch are influenced by their proximity to other patches of a similar type.

Mean nearest neighbour distance is computed for all patches in a particular class or in a landscape. This is the average edge-to-edge distance between all patches of the class type, or all patches within the landscape. **Nearest neighbour standard deviation** is a second order statistic that indicates patch dispersion. A small standard deviation relative to the mean indicates a uniform or regular distribution of patches (in that class) across the landscape. A large standard deviation indicates an irregular, uneven distribution of patches. **Nearest neighbour coefficient of variation** measures the relative variation around the mean as a percentage of the mean.

A **mean proximity index** (MPI) is computed at patch level and at class level. At class level MPI measures the degree of isolation and fragmentation of the patches of that class, equalling the average proximity index for patches in the landscape. If mean patch index has a value of 0, there are no other patches of the same type in the landscape. The higher the MPI value, the less fragmented is that particular landcover class.

7.4.4.2 The interspersion and juxtaposition metric

The **interspersion and juxtaposition index** is applicable at both class and landscape levels. Each patch is evaluated for adjacency with all other patches types and the index measures the extent to which patch types are interspersed. Higher values indicate landscapes where the patches are equally adjacent to each other whereas low values characterise landscapes where the patch types are poorly interspersed. Poor interspersion of a class indicates that this class is found next to the patches of one or two classes in particular rather than being found next to all types of patches equally. Poor interspersion of a class would indicate association with another class in the landscape, that is where the poorly interspersed class is found, it is likely that one of the other classes will most often be found next to it. The interspersion index is a relative index indicating the observed level of interspersion as a percentage of the maximum possible dispersion given the total number of patches.

7.5 Landscape ecological quantification of the study area

The six NDVI subset images of the field area subsets as defined in Chapter 6 were used for a landscape ecological investigation of the field area. Two of the six subsets comprise the whole of the study area (these two images being the Infierno catchment and the Mocatán catchment). The other four subsets are Malaguica, Mocatán badlands, Juan Contreras badlands and Sorbas. Results are reported for all six areas as, by using the subsets, the influences of different cover types in different parts of the landscape can be better observed.

7.5.1 FRAGSTATS method

All of the NDVI image subsets were clumped and sieved using ERDAS Imagine routines before use in FRAGSTATS in order to extract all patches of less than five pixels. It was decided to remove all ‘patches’ below five pixels in size as such small patches create a lot of background ‘noise’ and obscure the contribution of the larger patches to the functioning and structure of the landscape. All six clumped and sieved subsets were exported from ERDAS Imagine as .gis files.

The .gis files were used as input to FRAGSTATS, which also required a number of other input values including grid cell size, (in this case was five metres), values for interior background cells (zero), the maximum possible number of patch types (six), use of diagonals in patch finding (yes), search radius for proximity index (100m), calculate nearest neighbour density (yes), and output patch and class level metrics as well as landscape level statistics (yes).

FRAGSTATS output consisted of four files for each of the six input subsets. Three of these contained patch, class and landscape metrics respectively in an ASCII format allowing direct import into Microsoft Excel for analysis. The fourth was a printable output of metrics for all patches, classes and the landscape of each subset. The analysis of the landscape was carried out on a class and landscape basis, not on a per-patch basis as there were up to 3000 individual patches in some of the subsets.

7.5.2 Buffering of classes method

A routine undertaken to complement the FRAGSTATS statistics was to buffer all pixels of the individual classes by 10m (two pixels) either side to investigate the frequency with which a class was found adjacent to the other classes in the study area. This information can be used to investigate whether there is a smooth environmental gradient between classes 1 and 6 or whether class 1 and therefore the erosion in the catchments is cutting directly into the more densely vegetated areas. It is hypothesised that if there was a smooth environmental gradient between bare and most densely vegetated landcover this would be shown in the buffering statistics as a class always being next to its immediate neighbours (e.g. class 3 would always be next to classes 2 and 4, and class 6 would always be surrounded by class 5). However, if there were sharp environmental gradients, then dense classes would be next to sparse or bare classes, indicating that erosion is encroaching on dense vegetation. This routine can also be used to investigate the hypothesis that class 6 is actually the ‘core area’ of class 5 in landscape ecology rather than a true individual class. The buffering results complement those of the Interspersion and Juxtaposition index. Which indicates the degree of interspersion of a class, but does not show whether poorly interspersed classes are associated with another class in particular. Using the buffering these relationships can be discovered.

The steps undertaken to acquire these statistics were as follows. Each class in each subset was buffered by two pixels using the ERDAS Imagine search routine. The buffered area was then used to mask out the areas of interest in the subset using the ERDAS Imagine mask routine. Pixel statistics were taken from the raster attributes table associated with the masked file, and imported into Excel. In Excel the actual numbers of pixels for each class were converted into percentages.

7.6 Results

It should be noted that the discussion of the FRAGSTATS results concentrates mainly on the results for the class analysis of each subset (Tables 7.1 and 7.2) rather than the analysis of the subsets as a whole (Tables 7.3 and 7.4). Class metrics will be discussed in the following section with occasional reference to whole landscape metrics when an overview of the study area is needed.

7.6.1 Area metrics

All class metrics are displayed in Tables 7.1 and 7.2 (these six subsets are the same as those described in Chapter 6 and they are illustrated Figures 6.6 and 6.7 which are presented here as Figures 7.4 and 7.5 for ease of reference). There are marked differences between the two catchments. The Mocatán catchment appears to show a smooth environmental gradient between class 1 with the highest proportion of cover and class 6 having the lowest proportion of cover. The Infierno catchment in contrast has a low proportion of class 1 and the highest of class 5 cover (associated with a small amount of class 6).

The catchments were subset into a total of four subsets to allow the investigation of the landscape metrics in these areas of differing cover types. Each subset has a similar landcover pattern throughout but is markedly different from the other subsets. Two are in the Infierno catchment (Malaguica and Juan Contreras badlands), one in the Mocatán catchment (Mocatán badlands) and one subset across both catchments (Sorbas subset).

The Mocatán badlands subset is slightly more bare than the Mocatán catchment with the more sparsely vegetated areas having higher cover percentage values and the densely vegetated areas having slightly lower percentage values than in Mocatán catchment as a whole.

Class 2 has the highest proportion of cover in the Juan Contreras badlands with classes 1 and 3 having the second highest cover proportions. Class 6 again has the lowest cover proportion and class 5 is also quite low indicating that Juan Contreras badlands is an area of sparse vegetation.

The Malaguica area of the Infierno catchment has very different cover percentages to the Infierno catchment as a whole. Class 3 has the highest cover percentage with classes 2 and 4 having the next highest. Classes 1 and 6 have the lowest landcover proportions indicating that this subset is moderately vegetated with few areas of either very sparse or very dense vegetation.

The Sorbas subset is very different to the other subsets. It appears that this type of cover pattern influences the cover proportions in the whole of the Infierno catchment as it has a very high percentage cover of class 5 (over 50%) and a very low percentage of class 1. This is the only subset in the study area to have over 10% cover of class 6. The Sorbas subset can be characterised as having a dense to very dense cover of vegetation.

The largest patch metric is a measure of the percentage of the landscape that the largest patch of each class covers (Table 7.1). The largest patch at a catchment level is found in the Mocatán catchment where a patch class 1 comprises over 15% of the landscape. This is in contrast to the Infierno catchment where a patch of class 5 is the largest patch at 4.4% of the landscape. The rest of the classes in the Mocatán catchment have small largest patch percentages compared to class 1. Class 3 in the Infierno catchment has a percentage cover of the landscape of 3.6%, and the other largest patches for the classes are all small. In the Mocatán badlands and Juan Contreras badlands the largest patch (which is class 1 in both cases) makes up 14.3 and 14.1% of those landscapes respectively. In Malaguica, a patch of class 3 comprises 13.7% of the landscape and in Sorbas, the largest patch is of class 5 making up 16.1%. In all cases except in the Juan Contreras badlands the largest patch is in the class that has the highest percentage cover in the landscape and hence similar conclusions can be drawn as to those concerning class area.

		Area metrics			Patch density					Edge metrics	
	Class	Class Area ha	% of landscape	Largest patch Index %	Number of patches	Patch density #/100ha	Mean Patch size ha	Patch size SD ha	Patch size CV %	Total edge m	Edge Density m/ha
Infierno cmt	1	13.6	7.7	1.3	169.0	96.3	0.08	0.21	266.3	24245.0	138.1
Infierno cmt	2	28.9	16.5	1.5	429.0	244.4	0.07	0.18	268.0	71275.0	406.0
Infierno cmt	3	34.3	19.5	3.6	560.0	319.0	0.06	0.27	448.0	100850.0	574.5
Infierno cmt	4	36.7	20.9	0.4	678.0	386.2	0.05	0.10	183.9	117750.0	670.7
Infierno cmt	5	48.9	27.9	4.4	418.0	238.1	0.12	0.49	416.3	100105.0	570.2
Infierno cmt	6	13.2	7.5	0.9	222.0	126.5	0.06	0.14	234.4	29235.0	166.5
Mocatán cmt	1	34.2	32.2	15.4	194.0	183.1	0.18	1.18	670.0	54350.0	512.9
Mocatán cmt	2	25.7	24.3	1.1	472.0	445.4	0.05	0.11	201.6	83555.0	788.5
Mocatán cmt	3	17.2	16.2	0.9	527.0	497.4	0.03	0.06	189.9	59745.0	563.8
Mocatán cmt	4	12.8	12.1	0.4	407.0	384.1	0.03	0.04	125.8	45310.0	427.6
Mocatán cmt	5	13.8	13.0	2.3	233.0	219.9	0.06	0.18	306.1	31990.0	301.9
Mocatán cmt	6	2.4	2.2	0.2	80.0	75.5	0.03	0.03	112.3	6940.0	65.5
Moc badlands	1	9.2	36.5	14.3	62.0	247.1	0.15	0.48	324.6	15660.0	624.2
Moc badlands	2	6.7	26.8	4.1	133.0	530.1	0.05	0.11	221.8	21970.0	875.7
Moc badlands	3	3.6	14.3	0.6	141.0	562.0	0.03	0.03	98.3	13595.0	541.9
Moc badlands	4	2.7	10.6	0.6	94.0	374.7	0.03	0.03	92.1	9150.0	364.7
Moc badlands	5	2.6	10.3	2.0	55.0	219.2	0.05	0.08	177.8	6020.0	240.0
Moc badlands	6	0.4	1.5	0.2	20.0	79.7	0.02	0.01	55.0	1325.0	52.8
Sorbas	1	0.6	1.5	0.1	23.0	61.0	0.03	0.01	50.5	1660.0	44.0
Sorbas	2	2.1	5.7	0.7	66.0	175.0	0.03	0.04	123.7	5665.0	150.2
Sorbas	3	3.2	8.5	0.3	130.0	344.7	0.02	0.02	90.6	11230.0	297.8
Sorbas	4	8.6	22.9	2.1	194.0	514.4	0.04	0.09	203.8	29430.0	780.4
Sorbas	5	18.9	50.0	16.1	75.0	198.9	0.25	1.01	402.0	34970.0	927.3
Sorbas	6	4.3	11.4	1.2	82.0	217.4	0.05	0.08	158.0	11325.0	300.3
J C badlands	1	3.3	20.5	14.1	29.0	177.7	0.12	0.42	362.5	5190.0	318.1
J C badlands	2	4.9	30.2	6.2	55.0	337.1	0.09	0.19	214.8	12825.0	786.0
J C badlands	3	4.0	24.5	2.2	72.0	441.2	0.06	0.07	126.7	12225.0	749.2
J C badlands	4	2.2	13.5	1.4	75.0	459.6	0.03	0.03	99.8	7425.0	455.0
J C badlands	5	1.5	9.1	2.4	45.0	275.8	0.03	0.06	176.5	3955.0	242.4
J C badlands	6	0.4	2.3	0.4	15.0	91.9	0.03	0.02	70.4	1000.0	61.3
Malaguica	1	1.9	4.2	0.6	53.0	115.8	0.04	0.05	127.0	4990.0	109.1
Malaguica	2	9.3	20.3	3.0	146.0	319.1	0.06	0.14	223.9	24860.0	543.3
Malaguica	3	14.9	32.5	13.7	156.0	341.0	0.10	0.50	526.3	41825.0	914.1
Malaguica	4	10.6	23.1	1.7	230.0	502.7	0.05	0.09	192.4	36020.0	787.2
Malaguica	5	7.8	17.0	1.4	142.0	310.4	0.05	0.10	183.7	19640.0	429.2
Malaguica	6	1.4	3.0	0.3	43.0	94.0	0.03	0.03	88.6	3735.0	81.6

Table 7.1 Class area, patch density, size, variability and edge metrics for all six NDVI subsets

		Shape metrics		Nearest neighbour metrics				
	Class	Landscape Shape index	Mean Shape Index	Area weight mean shape	Mean nearest neighbour distance m	Nearest neighbour index SD m	Nearest neighbour CV 5	Mean Proximity Index	Interspersion and Juxtaposition index %
Infierno cmt	1	34.2	1.8	3.2	17.7	27.3	154.1	52.4	37.5
Infierno cmt	2	43.1	2.1	4.3	10.0	11.4	113.7	94.2	65.8
Infierno cmt	3	48.7	2.2	6.2	7.8	5.9	75.3	155.8	68.3
Infierno cmt	4	51.8	2.2	3.9	7.6	5.9	78.0	69.1	62.4
Infierno cmt	5	48.5	2.2	7.2	8.1	7.6	94.9	297.3	62.8
Infierno cmt	6	35.1	1.8	2.7	18.0	18.9	104.5	31.7	32.5
Mocatán cmt	1	32.5	1.9	8.9	9.8	9.5	96.7	1051.0	32.6
Mocatán cmt	2	39.6	2.2	4.1	6.5	4.5	69.7	87.3	61.7
Mocatán cmt	3	33.8	1.9	3.0	8.0	6.0	74.2	34.5	74.6
Mocatán cmt	4	30.3	1.9	2.6	10.1	10.6	105.9	21.6	72.8
Mocatán cmt	5	27.1	1.9	4.3	12.9	14.8	114.3	51.5	73.4
Mocatán cmt	6	21.0	1.5	1.9	27.5	27.4	99.4	8.6	32.0
Moc badlands	1	18.6	1.9	6.0	6.6	3.7	55.7	419.2	34.1
Moc badlands	2	21.7	2.2	4.2	6.1	2.6	43.6	83.4	59.0
Moc badlands	3	17.5	1.9	2.3	8.5	6.1	71.5	18.1	74.1
Moc badlands	4	15.3	1.9	2.3	12.3	8.9	72.4	11.9	75.9
Moc badlands	5	13.7	1.9	3.1	15.7	13.5	86.0	33.3	80.5
Moc badlands	6	11.4	1.4	1.6	29.7	28.4	95.6	4.6	24.1
Sorbas	1	12.5	1.7	1.9	36.0	36.5	101.6	3.9	59.8
Sorbas	2	14.1	1.9	2.4	14.4	19.6	136.6	13.5	81.3
Sorbas	3	16.4	1.8	2.2	11.6	13.8	118.8	14.5	73.1
Sorbas	4	23.8	2.0	3.8	6.9	4.4	64.3	74.5	49.6
Sorbas	5	26.0	2.4	11.2	5.7	2.1	37.1	1084.6	58.3
Sorbas	6	16.4	1.8	2.6	13.6	13.1	96.1	27.9	26.7
J C badlands	1	12.1	1.8	4.4	11.4	8.4	73.5	119.5	32.2
J C badlands	2	16.8	2.4	4.9	6.5	4.4	67.7	126.7	61.6
J C badlands	3	16.5	2.2	3.4	6.8	7.0	102.6	54.5	61.9
J C badlands	4	13.5	1.9	2.3	8.4	6.0	71.6	18.8	69.5
J C badlands	5	11.3	1.8	2.4	14.4	13.5	93.9	8.4	75.3
J C badlands	6	9.5	1.5	1.7	36.9	17.9	48.6	0.4	37.0
Malaguica	1	14.1	1.6	2.0	21.7	31.8	146.2	13.9	30.2
Malaguica	2	21.4	2.0	3.9	9.1	6.1	67.2	65.2	55.7
Malaguica	3	27.7	2.3	9.8	6.3	3.1	48.1	493.4	62.6
Malaguica	4	25.6	2.0	3.7	7.0	5.4	76.9	64.2	59.6
Malaguica	5	19.5	1.9	3.1	10.1	10.8	106.8	47.2	61.6
Malaguica	6	13.6	1.6	1.9	18.3	25.9	141.6	12.3	45.1

Table 7.2 Class shape metrics, nearest neighbour metrics and contagion and interspersion metrics

7.6.2 Patch density, patch size and variability

The metrics for patch density, patch size and variability are shown in table 7.1. Mean patch size in all subsets for all classes is small (between 0.02 ha and 0.25ha). Within this range there are some variations within and between subsets with the largest mean patch size being for class 5 in the Sorbas subset at 0.25 ha and the smallest mean patch size being 0.02 for class 6 in the Mocatán badlands and class 3 in the Sorbas subset. This indicates that the Sorbas subset has the widest variability in patch size. However, mean patch size is not a particularly good measure on its own as, for example, 10 patches of 10ha in size gives a mean value of 10ha as does 5 patches of 15ha plus 5 patches of 5ha patches indicating that the mean value gives no information about the variation in patch size. To identify the range of patch sizes, patch size standard deviation is used. In almost all cases those classes with the smallest mean patch size have the smallest standard deviation and those with the largest patch sizes have the largest standard deviation.

The average overall landscape (as opposed to class) level patch size in the study area catchments shows little variation (Table 7.3) although the patch size standard deviation (PSSD) indicates that there is more variation in size of patches in the Mocatán catchment than in the Infierno catchment. The patch size coefficient of variation (PSCV) shows a large difference between the Infierno and Mocatán catchments. At the landscape scale the Mocatán catchment has the greatest variation in size of all patches with a PSCV score of 702. This metric measures variability of patch size about the mean so it is therefore not necessary to know mean patch size to interpret the coefficient of variation (McGarigal and Marks, 1995). PSCV is derived by dividing the patch standard deviation by the mean patch size. Patch size coefficient of variation (PSCV) would equal zero if all patches in the landscape were the same size, or there was only one patch. The higher the score, the more variation there is in patch size indicating that patches in the Mocatán catchment have more variation in their size than those of the Infierno catchment. The Infierno catchment as a whole appears to be less fragmented. Its patch density is lower than the Mocatán catchment patch density.

	Total Area (ha):	Largest Patch Index %:	# of patches:	Patch Density (#/100 ha):	Mean Patch Size (ha):	Patch Size SD (ha)	Patch Size CV (%):	Total Edge (m):	Edge Density (m/ha):
Infierno cmt	175.55	4.35	2476	1410.4	0.07	0.27	375.12	221730	1263.04
Mocatán cmt	105.96	15.38	1913	1805.36	0.06	0.39	702.21	140945	1330.14
Moc badlands	25.09	14.27	505	2012.95	0.05	0.18	371.11	33860	1349.68
Sorbas	37.71	16.06	570	1511.44	0.07	0.38	573.09	47140	1249.98
J C badlands	16.32	14.14	291	1783.36	0.06	0.16	294.03	21310	1305.96
Malaguica	45.75	13.71	770	1682.88	0.06	0.24	410.89	65535	1432.3

Table 7.3 Landscape area, patch density and edge metrics

	L/S Shape Index:	Mean Shape Index:	Area-Weighted MSI	Mean Nearest Neigh-bour (m):	Nearest Neighbour SD (m):	Nearest Neighbour CV (%):	Mean Proximity Index:
Infierno cmt	71.46	2.12	5.18	9.8	12.06	123.62	127.09
Mocatán cmt	53.56	1.96	5.27	9.7	11.13	115.02	148.83
Moc badlands	27.64	1.92	4.22	10	10.31	103.56	84.51
Sorbas	31.0	1.93	7.11	10.8	14.51	134.32	177.11
J C badlands	22.08	2.0	3.77	10.3	11.07	107.15	55.49
Malaguica	36.46	1.99	5.48	9.5	12.83	135.31	141.85

Table 7.4 Landscape shape and nearest neighbour metrics

Greater variability in patch size indicates less uniformity in pattern and may reflect differences in processes affecting the landscape (McGarigal and Marks, 1995). At a class level, the Mocatán catchment shows the greatest variation in PSCV with class 6 having the smallest size variation and class 1 the largest; the range between the two being 558. This is to be expected however as these classes have the smallest and largest patch size values respectively and patch size standard deviation respectively.

The differences in average patch size between the landscape subsets (Table 7.3) indicate that there is little variation in patch size across the landscape of the study area. The Mocatán badlands area has the smallest average patch size at 0.05ha, the Sorbas the largest at 0.07ha. The Juan Contreras badlands has a smaller variation in patch size as compared to the Malaguica subset. the Mocatán badlands have the greatest patch density as compared to the other subsets. This indicates fragmentation in the landscape. This is supported by the smallest mean patch size metric. The Sorbas subset has the highest PSCV of the four landscape subsets, the Juan Contreras badlands the lowest. At a class level, the Mocatán badlands show the smallest difference in PSCV with all the scores for this metric being within a range of 275. The scores are all lower here indicating an area with more similar sized patches throughout each class. The PSCVs of the six classes in the other subsets lie between these results. The Juan Contreras badlands subset has the smallest variation in patch sizes of all the study area subsets. The Mocatán badlands and Malaguica have similar PSCV scores at around 400.

7.6.3 Edge metrics

Only two edge metrics were calculated in the FRAGSTATS run, these being total edge and edge density which is amount of edge (m) per hectare. Edge density, the more useful measurement due to its being standardised, is used in the following analysis of edge in the study area. Classes in the study area subsets with high edge values are likely to be more fragmented than classes with less edge. It could be assumed that all things being equal, the class with the greatest percent of the landscape would have the most edge. However this is not the case in some of the subsets. Edge is a measure of fragmentation in the landscape when looked at in conjunction with class area and number of patches. A class which has a high edge density but less class area than another could be assumed to be more fragmented with smaller patches enclosing less area. A notable case in the six subsets is class 2 in the

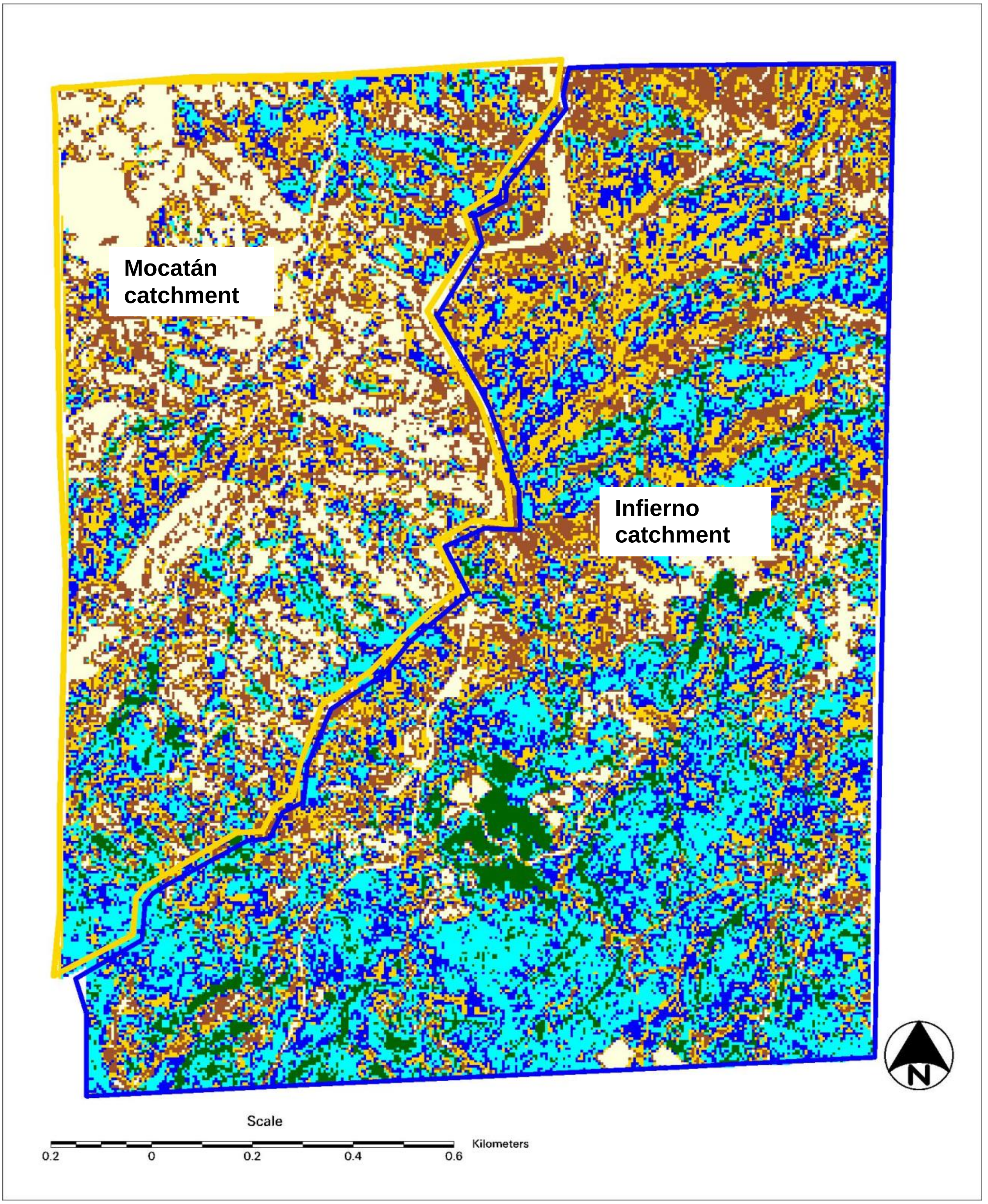


Figure 7.4 Copy of Figure 6.8 Catchment NDVI subsets

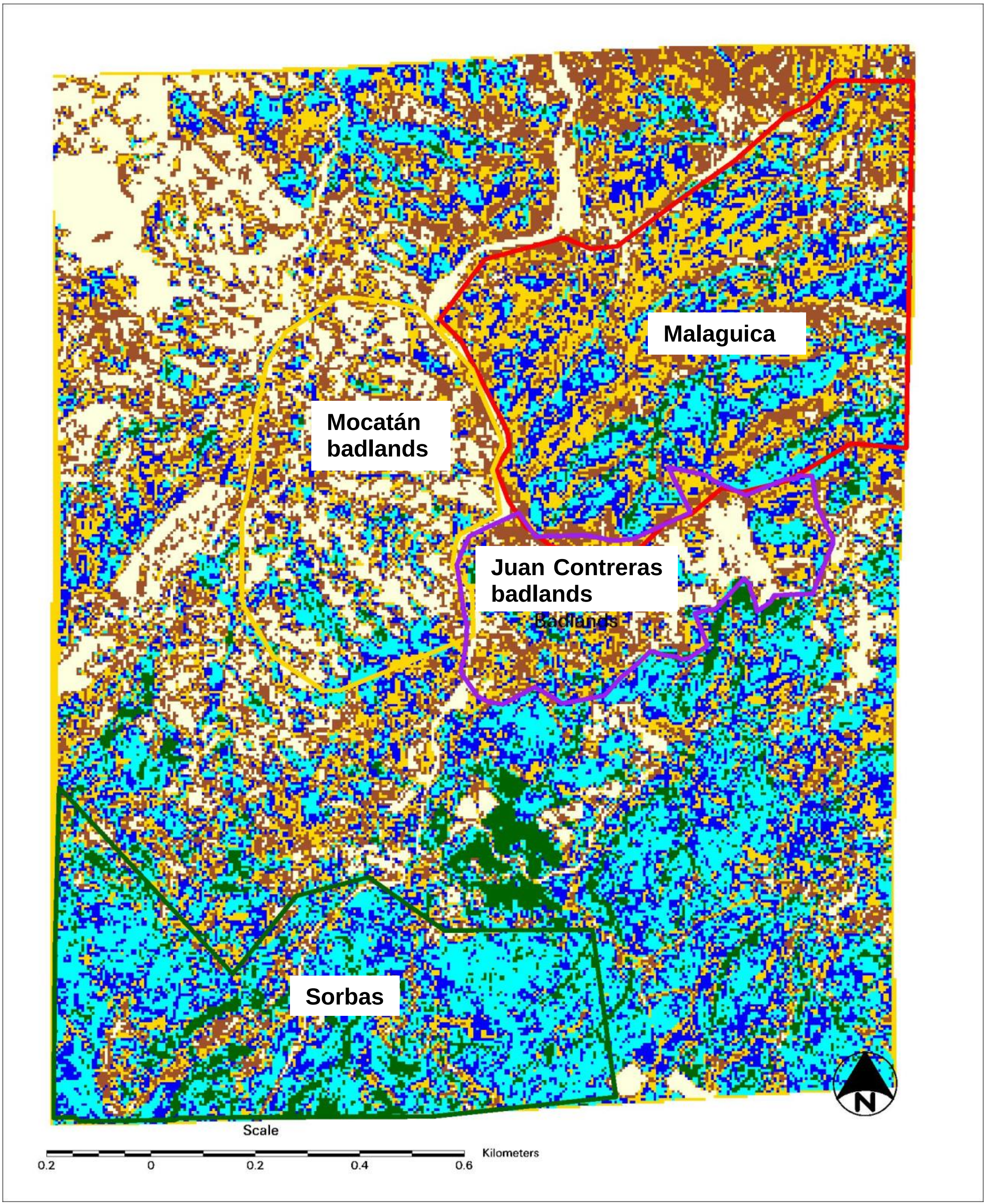


Figure 7.5 Copy of Figure 6.9 Sub-catchment clustered NDVI subsets

Mocatán catchment which has the highest edge density but does not make up the highest proportion of the subset or have the highest patch density. This indicates that this class has a lot of edge and very little core area. However edge metrics as a measure of landscape structure are more useful when included in the calculation of shape metrics, as edge is one of the statistics included in the calculation of shape indices. These are discussed below.

7.6.4 Shape metrics

The shape indices that FRAGSTATS calculates are based on perimeter-area relationships. The landscape shape index will not be used as it can give results that are not meaningful if landscape boundary is included as edge, which in the raster images input into FRAGSTATS is the case. As discussed in section 7.4.2 the mean shape index (MSI) indicates how close the patches in a class or landscape are to square, when a raster image is being investigated. The metric is the average of the shape index for each patch in the landscape or class. The closer the figure to 1, the closer the patches in the class or landscape are to square. Another metric, the area-weighted mean shape index, allocates weight to larger patches. The area-weighted mean shape index (AWMSI) gives better separation of values in the class and landscape metrics (Tables 7.2 and 7.4) and will be used here to investigate patch shape.

At a catchment level, class 1 in Mocatán and class 5 in Infierno are the furthest from a score of 1 indicating that they are the most irregular in shape. Both these classes are often found in channel bottoms in their respective catchments and so the patches are linear in nature and AWMSI has picked these out as being the least regular classes. Class 6 is the nearest to square in both catchments, but is found in very small amounts in both catchments and makes up so little of the landscape that many of the patches will be only a few pixels in size.

The AWMSI of class 5 in the Sorbas subset is the furthest from 1 of all the subsets, indicating the most irregularly shaped patches. Class 5 in this subset is often found in linear patches either along ridges or in channel bottoms. Class 3 in the Malaguica subset has a high AWMSI score for class 3 which can be found running along the tops and sides of ridges in this subset. The most regularly shaped class patches in the subsets are those of class 6 in all but the Sorbas subset where class 1 is the most regular in shape. Class 6 makes up a small percentage of the landscape in all but the Sorbas subset and will have patches made up of small numbers of pixels which reduces the chance for irregular shaped patches to occur, and this effect is enhanced by the AWMSI weighting of larger patches. Class 1 in the Sorbas subset is associated with cleared agricultural terraces which are square of rectangular in shape giving rise to a metric score that is close to one. The classes in the Juan Contreras badlands have similar scores, none of which are very high. Classes 1, 2 and 3 are more irregular than 4, 5 and 6, but the overall differences between regular and irregularly shaped are small. This is reflected in the non-linear appearance of the landscape in this particular subset. At a landscape level, the Sorbas subset has the highest overall AWMSI score indicating that the patches in this landscape are the most irregular overall. The Juan Contreras badlands has the most regular patches overall, confirming it as having the most regular patch shapes of all the subsets. McGarigal and Marks (1995) indicate that the shape metrics discussed above are not indicative of patch morphology, but their use here does appear to distinguish between linear and non-linear patches quite well.

7.6.5 Nearest neighbour metrics

Mean nearest neighbour (MNN) is the average distance at the class level, between patches of the same class. MNN score at the landscape level uses the class MNN scores and takes the average to give the overall score for that landscape.

At the catchment level class 6 has the highest MNN score, indicating that this small class has the greatest distance between patches. Class 4 has the lowest average distance between patches in the Infierno catchment, and in the Mocatán catchment class 2 has the lowest distance between patches. At the catchment level, the highest proportion of cover is not matched by lowest MNN scores and only the Mocatán catchment has lowest percentage cover of landscape with highest MNN score for class 6.

Results for the four subsets at class level indicate that in three out of the four subsets cases those classes which cover the least area in the landscape have the highest nearest neighbour scores (Table 7.2). The exception to this is found in the Malaguica subset where class 1 is more fragmented than class 6 even though class 6 has the least amount of cover. The opposite also appears to hold true in comparison with the catchment level. In three of the four subsets, the class with the highest cover has the lowest nearest neighbour values. In the Mocatán badlands and Juan Contreras badlands class 2 has the lowest MNN, at 6.1m and 6.5m respectively. Class 2 appears to be a class that has its patches in close proximity to each other in these particular subsets. Malaguica's lowest MNN score is class 3 at 6.3m. The Sorbas subset class 5 has the lowest MNN score of 5.7m. All these classes with low MNN scores also have low standard deviations.

The nearest neighbour coefficient of variation (NNCV) measures relative variation of MNN distance around the mean (variability of nearest neighbour distance as a percentage of the mean (McGarigal and Marks, 1995)). The greater the NNCV score the more irregular is the distribution of patches of a particular class, or of all patches in a landscape. The scores produced by this metric indicate that irregularity of distribution is not necessarily a function of a high MNN score. In the Infierno catchment class 1 is the most irregularly distributed class. This can be seen in the clustered NDVI image (Fig.7.4), class 1 is not distributed widely across the landscape, but is concentrated in several places. Class 3 is the most regularly distributed class in the Infierno catchment, its NNCV score being less than half that of class 1. Class 5 is the most irregularly distributed class in the Mocatán catchment. This is again fairly obvious from the clustered image (Fig 7.4) as most of the class 5 is concentrated in one or two places in the catchment, i.e. isolated but also locally fragmented. Class 2 is the most regularly distributed class in the Mocatán catchment. The difference in regularity of distribution for all classes is less than that for the Infierno catchment, indicating that the patches in the Mocatán catchment are slightly more regularly distributed than in the Infierno catchment. This is supported by the landscape NNCV scores found in Table 7.4 where the score for the Infierno catchment is higher than that of the Mocatán catchment.

Class 2 is the most regularly distributed class in the Mocatán badlands and class 6 the most irregularly distributed class. The difference between the most regular and most irregular distribution of patches in this subset is small and of all the subsets this has the lowest NNCV landscape score. This indicates that the landcover patches in this catchment are more regularly distributed across the landscape than patches in any of the other subsets. The Sorbas and Malaguica subsets have the least regularly distributed patches in the landscape as a whole, and the differences between the most regularly distributed classes and the least regularly distributed classes are much greater.

7.6.6 Mean proximity index

The nearest neighbour metrics for all subsets provide an insight into how easily material, energy and species flows between patches of the same class throughout the subsets, with close proximity of patches indicating ease of flow. However, as these figures are averaged across the whole of a subset, large NNCV figures may be obtained where there is a high density of patches of one class found only in a small part of the subset (for example class 5 and 6 in the Mocatán badlands subset are found mostly around Cerro de Juan Contreras), but within this small area containing the patches of those particular classes, flows may more easily take place. The Mean Proximity Index (MPI) calculates the degree of isolation and fragmentation of class types in a different way to nearest neighbour metrics. A search area radius is provided by the user of FRAGSTATS for calculating proximity of patches of the same class (in all cases the proximity given was 100m) and a score of 0 is achieved if there are no other patches of that class within the radius. At class level this score is averaged for all patches of that class. The higher the score, the more patches of the class in question are found in the radius, the higher the proximity and the more easily flows can take place between patches of the same class.

The MPI shows different classes as having close proximity than those found to be close by the NNCV. It is interesting to note that in every case the class with the highest MPI value also has the highest class area and the class with the lowest MPI has the lowest class area value (see Tables 7.1 and 7.2). However this does not seem to be a consistent relationship as the intervening classes are not ranked by percentage of landscape area. This indicates that the MPI does have a useful function in describing the landscape and is not just an indicator of class area.

MPI scores at catchment level indicate that class 1 in the Mocatán catchment has a very low fragmentation compared to the other classes in that catchment and when compared to classes in the Infierno catchment. The score of 1051 for this class is much greater than that of class 2 (87) indicating that the rest of the classes in this catchment are suffering considerable fragmentation. In the Infierno catchment, the highest score is that of class 5 with 297, the next highest being class 3 (155). This indicates that the classes are all more fragmented than class 1 of the Mocatán catchment, but are less fragmented overall. This is not borne out on the landscape scale with 127 for the Infierno catchment and 148 for the Mocatán catchment, but the extremely large MPI score for class 1 of the Mocatán catchment is likely to be skewing the figures for the Mocatán catchment as a whole.

At the subset level, the Sorbas subset has an extremely high MPI value for class 5 of 1084 indicating low fragmentation and ease of energy and material flows in this class. The rest of the classes in the Sorbas subset are very fragmented, none of them having a value above 75. Malaguica and the Mocatán badlands each have one class with a score of over 400, again indicating fairly low fragmentation of these classes (classes 3 and 1 respectively), but not as low as in the Sorbas subsets. The other classes in these two subsets all have MPI scores below 100, however, the differences in MPI scores is less than in the Sorbas and Mocatán catchment subsets.

The Juan Contreras badlands has relatively low MPI values for all classes. There are two classes with MPI scores of over 100 in Juan Contreras badlands and the variation in MPI scores is smaller than for the other subsets indicating that classes in these subsets are overall, more fragmented than the classes in the other subsets.

7.6.7 Interspersion and Juxtaposition

Table 7.2 shows the class interspersion and juxtaposition (IJI) scores for the two catchments and four subsets. It can be seen that classes 1 and 6 in both catchments are more poorly interspersed than the other four classes. The other four classes are fairly evenly interspersed in the Infierno catchment, all having interspersion scores of between 62 and 68%. In the Mocatán catchment, there is more variation in the interspersion scores with class 3 being 13% more interspersed than class 2. The low scores for classes 1 and 6 in both catchments may be an artefact of their position at either end of the NDVI clustering. This means that they are more likely to only be associated with their one neighbouring class rather than having two neighbouring classes as the clustered NDVI image is showing a gradient of vegetation cover.

At the subset level, class 6 is the most poorly interspersed in all but Malaguica, where class 1 is very poorly interspersed. Class 5 is particularly well interspersed in the Mocatán badlands and Juan Contreras badlands, and class 2 has a very high interspersion score in the Sorbas subset indicating that patches of these classes are found adjacent to all other classes in these subsets. The IJI can be better interpreted in light of the buffering statistics which will be reported in the next section where the scores can be related to classes.

7.7 Buffering of classes results

As the six classes are simply divisions of the range of NDVI values, individual pixels might be expected to be found adjacent to pixels of the same or an immediately neighbouring class in areas where environmental gradients are gentle, whereas adjacency to pixels of more distant classes would represent sharper environmental contrasts. The buffering of classes was undertaken to investigate the environmental gradients in each of the subsets to ascertain how the landscapes differ. These class adjacencies within a 10m buffer are shown as absolute numbers of pixels and percentage class frequencies in Table 7.5. A 10m buffer distance was chosen as the investigation was only into immediate adjacency, and the buffer distance had to be a multiple of the 5m pixel size.

The adjacency values for all classes in all subsets are presented as line graphs in Figure 7.6 in the form of percentage adjacency plotted by class distance. For example if class 3 is under investigation, self adjacency is the number of pixels of class 3 that are next to other pixels of class 3, a one class distance is when class 3 is next to either classes 4 or class 2, a two class distance is when a class 3 pixel is next to class 1 or class 5 and a three class distance is when the class 3 pixel is next to class 6. Self-adjacency indicates high connectivity within a class whilst adjacency to other, especially more distant, classes can be taken to indicate fragmentation. A line depicting the average class distance for the subset in question is shown in red. This line indicates the average environmental gradient in that particular subset. Distances from this line indicate how much each class conforms to the average environmental gradient.

7.7.1.1 Mocatán catchment

Class 1 pixels have a very high level of self-adjacency indicating high connectivity of this class and the large size of some of the patches of class 1 in this catchment (Figure 7.6 a). Class 5 pixels also have a high level of self-adjacency compared to the other distances, but to a lesser extent than class 1 pixels. In comparison with other classes in this catchment, class 5 and 6 pixels are adjacent to pixels at 3 and 4 distance (4 and 5 distance in the case of class 6) much more often indicating that pixels of classes 5 and 6 can be found next to classes 2 and 1. These figures indicate that classes 5 and 6 are interspersed with these two classes more often than would be expected demonstrating that the sparsely vegetated erosional areas are found at close proximity to dense vegetation.

Infierno catchment												
	class 1	**%**	**class 2**	**%**	**class 3**	**%**	**class 4**	**%**	**class 5**	**%**	**class 6**	**%**
class1	5562.0	36.6	4427.0	12.8	2450.0	5.3	1403.0	2.8	1052.0	2.2	344.0	2.0
class2	4978.0	32.7	11838.0	34.1	9365.0	20.3	5350.0	10.5	3311.0	7.0	786.0	4.5
class3	2207.0	14.5	9315.0	26.9	14939.0	32.4	10991.0	21.6	6581.0	13.9	1412.0	8.0
class4	1128.0	7.4	4792.0	13.8	10536.0	22.9	15342.0	30.1	11902.0	25.1	2490.0	14.2
class5	940.0	6.2	3451.0	9.9	7215.0	15.7	15201.0	29.8	19914.0	42.0	7044.0	40.1
class6	394.0	2.6	862.0	2.5	1550.0	3.4	2657.0	5.2	4683.0	9.9	5476.0	31.2
Mocatán catchment												
	class 1	**%**	**class2**	**%**	**class3**	**%**	**class4**	**%**	**class5**	**%**	**class6**	%
class1	13664.0	48.9	10825.0	33.6	5073.0	19.3	2184.0	10.9	1398.0	8.7	147.0	3.9
class2	8135.0	29.1	10288.0	31.9	7023.0	26.8	3802.0	18.9	2175.0	13.6	271.0	7.2
class3	3387.0	12.1	5629.0	17.5	6874.0	26.2	4383.0	21.8	2561.0	16.0	395.0	10.5
class4	1534.0	5.5	3094.0	9.6	4024.0	15.3	5106.0	25.4	3485.0	21.7	477.0	12.7
class5	1097.0	3.9	2085.0	6.5	2847.0	10.9	4148.0	20.6	5504.0	34.3	1526.0	40.5
class6	121.0	0.4	299.0	0.9	380.0	1.4	492.0	2.4	904.0	5.6	949.0	25.2
Mocatán badlands												
	Class1	**%**	**Class2**	**%**	**Class3**	**%**	**Class4**	**%**	**Class5**	**%**	**Class6**	**%**
class1	3735.0	46.4	3282.0	38.6	1556.0	25.5	768.0	17.2	506.0	15.6	65.0	8.9
class2	2390.0	29.7	2728.0	32.0	1737.0	28.5	974.0	21.8	493.0	15.2	52.0	7.1
class3	962.0	11.9	1284.0	15.1	1439.0	23.6	956.0	21.4	461.0	14.2	65.0	8.9
class4	545.0	6.8	736.0	8.6	810.0	13.3	1032.0	23.1	608.0	18.8	78.0	10.7
class5	375.0	4.7	447.0	5.3	505.0	8.3	671.0	15.0	1023.0	31.6	318.0	43.5
class6	45.0	0.6	54.0	0.6	57.0	0.9	64.0	1.4	149.0	4.6	153.0	20.9
Sorbas												
	Class1	**%**	**Class2**	**%**	**Class3**	**%**	**Class4**	**%**	**Class5**	**%**	**Class6**	**%**
class1	314.0	13.8	314.0	5.9	292.0	2.9	254.0	1.7	230.0	1.4	75.0	0.8
class2	648.0	28.4	1043.0	19.6	1005.0	10.1	958.0	6.3	805.0	4.9	311.0	3.4
class3	480.0	21.0	1190.0	22.4	1769.0	17.9	1729.0	11.4	1623.0	9.9	698.0	7.6
class4	392.0	17.2	1201.0	22.6	2867.0	29.0	4005.0	26.4	3913.0	24.0	1527.0	16.7
class5	362.0	15.9	1201.0	22.6	3185.0	32.2	6741.0	44.5	7729.0	47.4	4511.0	49.2
class6	87.0	3.8	360.0	6.8	785.0	7.9	1463.0	9.7	2014.0	12.3	2049.0	22.3
Juan Contreras badlands												
	Class1	**%**	**Class2**	**%**	**Class3**	**%**	**Class4**	**%**	**Class5**	**%**	**Class6**	**%**
class1	1421.0	34.2	1300.0	19.7	873.0	13.4	521.0	9.7	233.0	6.6	65.0	4.6
class2	1423.0	34.3	2126.0	32.1	1979.0	30.5	1289.0	23.9	598.0	17.0	144.0	10.2
class3	723.0	17.4	1718.0	26.0	1828.0	28.1	1605.0	29.8	892.0	25.4	237.0	16.9
class4	380.0	9.2	918.0	13.9	1098.0	16.9	1134.0	21.1	863.0	24.6	315.0	22.4
class5	168.0	4.0	452.0	6.8	562.0	8.7	650.0	12.1	721.0	20.5	434.0	30.9
class6	38.0	0.9	101.0	1.5	156.0	2.4	186.0	3.5	206.0	5.9	211.0	15.0
Malaguica area												
	Class1	**%**	**Class2**	**%**	**Class3**	**%**	**Class4**	**%**	**Class5**	**%**	**Class6**	**%**
class1	767.0	28.5	818.0	7.3	540.0	3.4	257.0	1.8	108.0	1.1	24.0	1.1
class2	1099.0	40.8	3801.0	34.2	3409.0	21.6	1824.0	13.0	887.0	9.4	202.0	9.1
class3	502.0	18.6	3914.0	35.2	5996.0	37.9	4632.0	33.0	2044.0	21.6	314.0	14.2
class4	208.0	7.7	1581.0	14.2	3708.0	23.4	4264.0	30.4	2759.0	29.2	373.0	16.8
class5	85.0	3.2	809.0	7.3	1837.0	11.6	2696.0	19.2	3129.0	33.1	751.0	33.9
class6	31.0	1.2	207.0	1.9	323.0	2.0	365.0	2.6	520.0	5.5	554.0	25.0

Table 7.5 Class adjacency frequencies (within 10m buffers) of each pixel in all subset

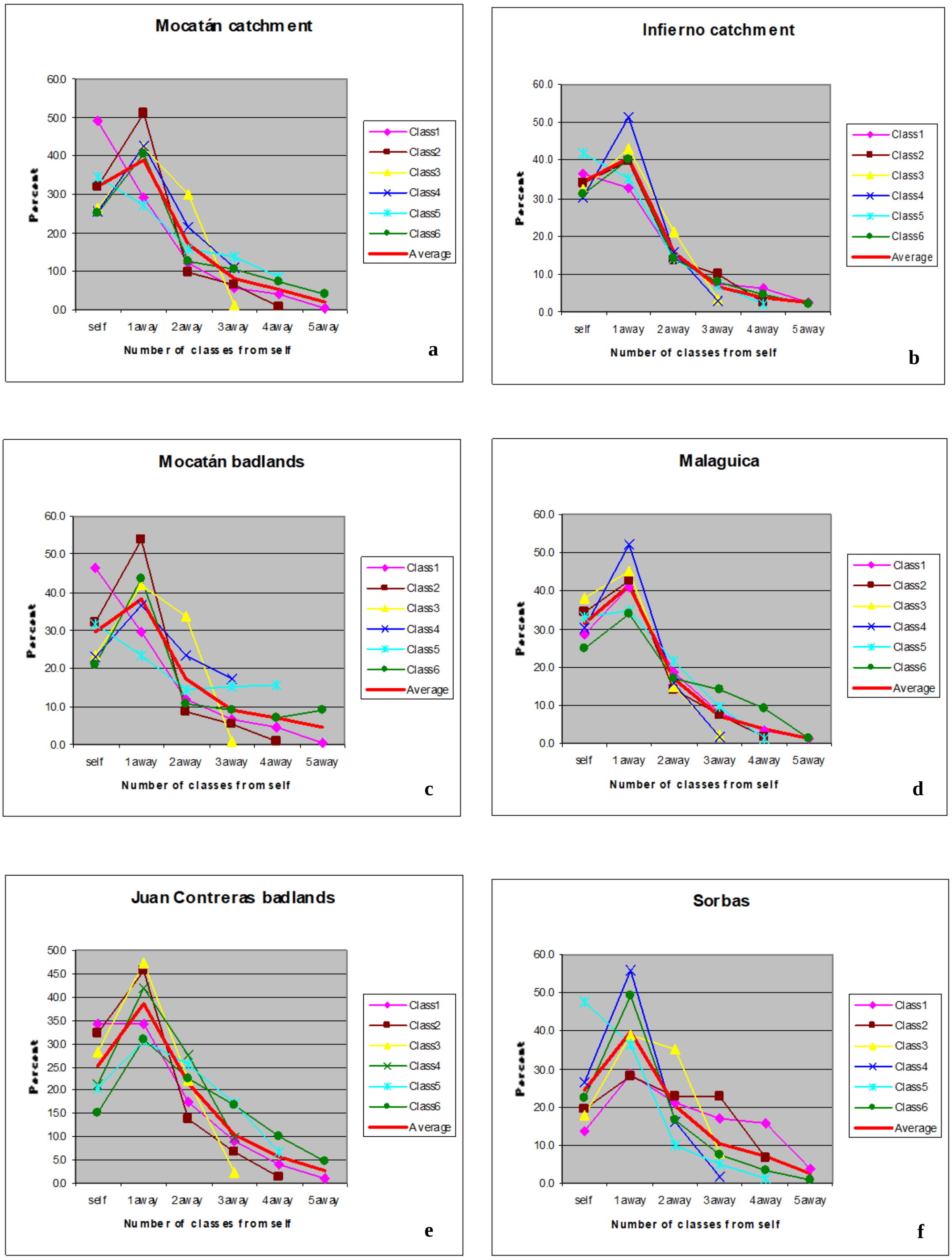


Figure 7.6 (a-f) Graphs for all subsets showing class adjacency

7.7.1.2 Infierno catchment

Pixels of classes 1 and 5 show higher levels of self-adjacency than pixels adjacent to other classes indicating that these two classes are the least fragmented in the catchment (Figure 7.6 b). Classes 3 and 4 pixels are found most often at distance 1 and to a lesser extent self adjacent and distance 2, evidence that they are part of a fairly smooth environmental gradient. Pixels of class 6 are most often next to class 5 pixels and rarely at a distance to other classes indicating it is likely that class 6 is at the dense end of quite a smooth environmental gradient in this catchment.

7.7.1.3 Mocatán badlands

Adjacency patterns show some variation (Fig 7.6c). The high self-adjacency of class 1 is likely to be related to the large patch sizes of this class. Class 5 pixels are most often found to be self adjacent, however, this self-adjacency score is low and reflects the fairly high percentage of pixels found in all the other distance categories. Class 5 pixels are found next to pixels of classes 1 and 2 as often as they are found adjacent to neighbouring classes. This is a very important indicator of sharp environmental gradients in this subset as this shows that class 5 is very often found next to the sparse erosional classes, and the figures for these adjacencies are higher than for the Mocatán catchment overall indicating that the Mocatán badland area is a focus for this type of class distribution. Class 6 pixels appear to be self-adjacent or surrounded by class 5 over 60% of the time. However, even the densest class in this subset has pixels which are adjacent to classes 1, 2 and 3 in 25% of its occurrences indicating a very sharp environmental gradient and confirming the pattern seen with class 5 pixels.

7.7.1.4 Malaguica

None of the classes in Malaguica are highly self adjacent indicating a different landcover pattern to that of the Infierno catchment as a whole (Figure 7.6 d). Class 5 shows high levels of pixel adjacency to itself, and at class distances of 1 and 2. The adjacency percentage then tails off quickly at a distance of 3 and 4 classes away indicating a much smoother environmental gradient than that of the Mocatán badlands, although not as smooth as that for the Infierno catchment as a whole. Class 6 shows a slightly sharper environmental gradient than class 5 as it is found adjacent to pixels of classes 3 and 2 in 25% of its occurrences. This is likely to be related to the position of class 6 in the agricultural terrace bottoms next to terrace erosion features. Classes 2, 3 and 4 show a compact relationship as all three are next to pixels of themselves of classes at distance 1 in about 80% of occurrences. This again indicates a fairly smooth environmental gradient in this subset.

7.7.1.5 Juan Contreras badlands

As in the Malaguica subset, none of the classes in the Juan Contreras badlands have very high self-adjacency figures, although pixels of class 1 are found next to each other almost as often as they are found next to class 2 pixels (Figure 7.6e). The environmental gradient between sparse and dense vegetation is much steeper in this area of badlands than in the Malaguica subset. This is demonstrated by the percentage adjacencies for classes 5 and 6 which display high figures for classes at 3, 4 and 5 distance. This indicates the juxtaposition of these two dense classes with areas of sparse and very sparse vegetation. Classes 2, 3 and 4 show higher levels of pixel adjacency with more distant classes even than in the Malaguica subset, supporting the view that the environmental gradient is very steep.

It is in fact comparable with the Mocatán badlands subset for many of the class adjacencies indicating a similar level of fragmentation of dense cover classes which are cut into by the erosional classes 1 and 2.

7.7.1.6 Sorbas

Class 5 has a very high pixel self-adjacency compared to the other classes in this subset (Figure 7.6f). Classes 4 and 6 also have high pixel self-adjacency figures relative to classes 1, 2 and 3. The figures indicate a smooth environmental gradient between dense and less dense vegetation with pixels of classes 4, 5 and 6 being self-adjacent and adjacent to classes at distance 1 over 70% of the time. Classes 1, 2 and 3 have low levels of self-adjacency and comprise only a small percentage of total cover in this subset. The figures indicate that these classes comprise small and fragmented patches with little connectivity to allow processes to take place between them. The overall adjacency figures for the Sorbas subset reveal a swap in pattern indicative of a change in processes working on this landscape compared to those at work in the other three subsets.

7.7.2 Overall comparison of the two catchments and four subsets buffering statistics

The graphs in Figure 7.7 (a-f) display the pixel adjacency figures for each class by subset or catchment. By displaying the figures in this format it is possible to identify differences and similarities in the patterns of pixel adjacency for each catchment or subset. It should then be possible to identify whether overall catchment pixel adjacencies are present in the subsets of those catchments or whether the signal from the subsets is 'drowned out' by the rest of the cover in the catchment.

The graph showing the class 1 pixel adjacencies (Figure 7.7a) shows that the adjacencies for the Mocatán catchment and the Mocatán badlands within that catchment are very similar. Class 1 comprises a large proportion of both catchment and subset, and this signal is reinforced by both. The Infierno catchment and Juan Contreras badlands have a similar pattern of class 1 pixel adjacency even though the proportions of this type of cover are very different in the Infierno catchment overall (8%) as compared to the Juan Contreras badlands (21% cover). Malaguica shows a different pattern to that of the Infierno catchment, with class 1 having more pixels adjacent to class 2 rather than being self-adjacent. This is likely to be a function of the very low percentage cover of class 1 in this subset (4%). The Sorbas subset (which covers parts of both the Infierno and Mocatán catchments) has a very different pattern for class 1 showing generally medium level adjacency with all other classes.

Mocatán badlands pixel adjacency figures are very similar to those of the Mocatán catchment overall for class 2, the badlands area obviously contributing to the pattern of the catchment for this class (Figure 7.7b). The pattern of class 2 in Juan Contreras badlands and Malaguica are also very similar to the pattern of class 2 adjacencies in the Infierno catchment as a whole. However, the pattern of class 2 adjacency for the Sorbas subset is very different to the other subsets and catchments overall. This different pattern is likely to be related to the low percentage cover of class 2 in the Sorbas subset, and the low cover means that the adjacency pattern does not influence the overall pattern for the two catchments this subset falls inside.

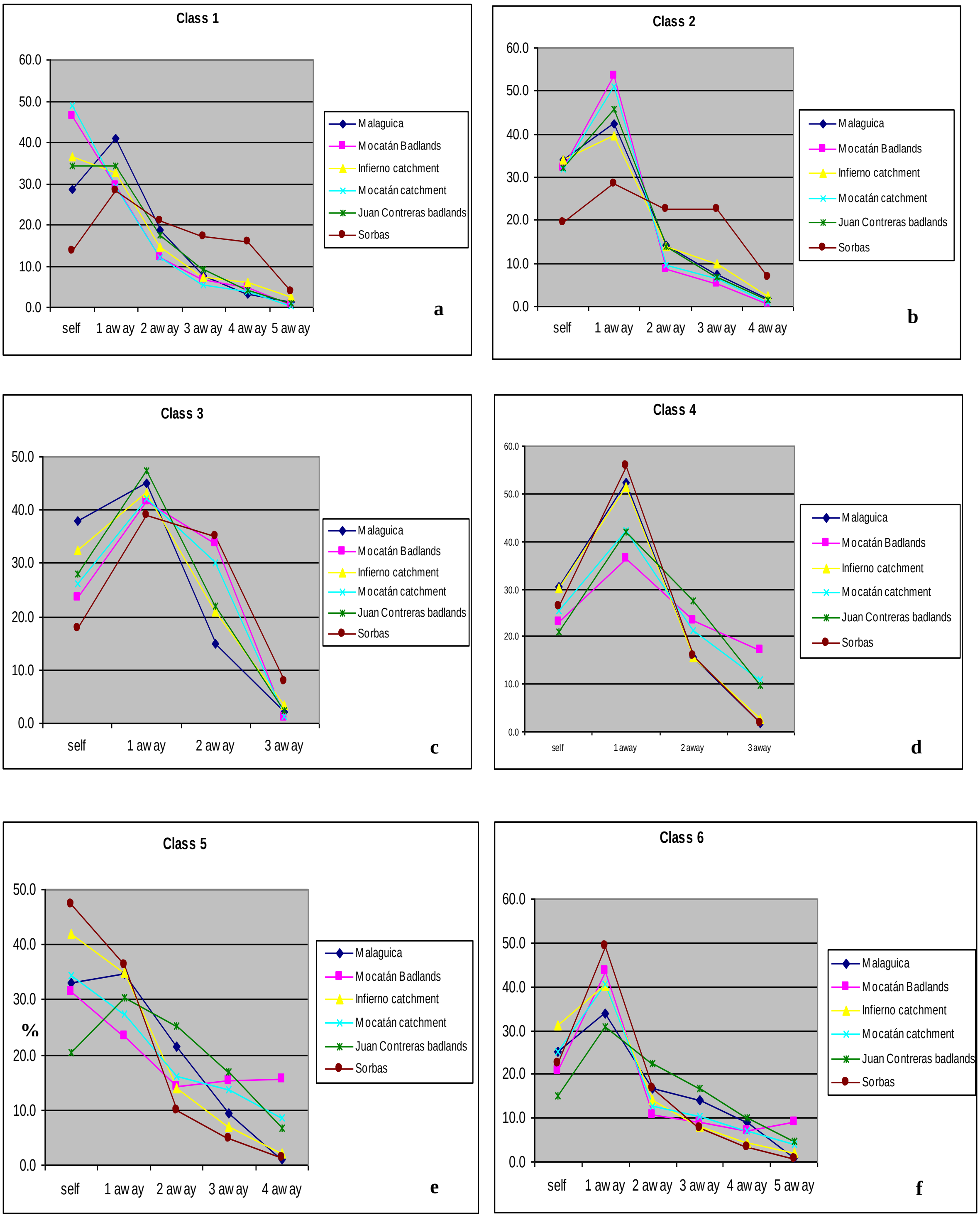


Figure 7.7 (a-f) Graphs showing comparison of subset pixel adjacency for each class. All figures in percent

The Mocatán badlands subset again has a similar class adjacency pattern to the Mocatán catchment as a whole for class 3 (Figure 7.7c). The Juan Contreras badlands have a similar pixel adjacency to the Infierno catchment as a whole, whereas the Malaguica subset differs somewhat with more pixels of class 3 being self-adjacent here than in the Infierno catchment as a whole. This is likely to be related to the high proportion of class 3 cover in the Malaguica subset where it makes up the largest class. Class 3 in the Sorbas subset shows a very similar adjacency pattern to that of the Mocatán badlands.

Class 4 in the Mocatán catchment has more pixels which are self adjacent and at distance 1 than the Mocatán badlands which has more pixels at distances 2 and 3 (Figure 7.7d). This is beginning to indicate the sharp environmental gradient in the Mocatán badlands which appears more extreme than in the Mocatán catchment as a whole. The pattern of class 4 pixel adjacency in Malaguica is very similar to that of class 4 adjacency in the Infierno catchment overall. However the pixel adjacency in the Juan Contreras badlands is quite similar to that in the Mocatán catchment as a whole, which indicates a sharper environmental gradient between sparse and dense vegetation in the Juan Contreras badlands than in the Infierno catchment as a whole. The Sorbas subset has a very similar pattern of class 4 adjacency to that of the Infierno catchment as a whole, which seems to indicate that the sharp environmental gradient in the Juan Contreras badlands is an aberration in the Infierno catchment as a whole.

The graph of class 5 pixel adjacency for the subsets (Figure 7.7 e) shows the most variation in pixel self adjacency pattern. The Mocatán catchment as a whole has more pixels which are self-adjacent and at distance 1 than the Mocatán badlands which have more pixels at greater distance. This reinforces the view that the Mocatán badlands have a particularly extreme environmental gradient compared to the Mocatán catchment as a whole. The Malaguica and Juan Contreras badlands subsets have very different pixel adjacency profiles to one another and when compared to the Infierno catchment. Neither of these subsets has high levels of self-adjacent pixels, but the Juan Contreras badlands shows the higher level of pixels at distances 2, 3 and 4 whilst Malaguica has more pixels at distance 1. The Sorbas subset follows the profile of the Infierno catchment. Class 5 in the Sorbas subset comprises 50% of the total cover, and 28% in the Infierno catchment, so it would appear that a lot of class 5 in the Infierno catchment is in areas which have similar cover patterns to the Sorbas subset, and this influences the pattern of class 5 pixel adjacency for the catchment as a whole.

In the Mocatán badlands, class 6 has more pixels which are found at distance 5 than class 6 in the Mocatán catchment as a whole, but overall they are very similar in profile (Figure 7.7f). Malaguica and Juan Contreras badlands have class 6 pixels which are more highly associated with classes at a greater distance than class 6 pixels in the Infierno catchment as a whole. The pattern of class 6 pixel adjacency in the Sorbas subset is again similar to the pattern of adjacencies in the Infierno catchment which indicates that it is the cover type of this subset that is influencing the class 6 pixel adjacency distribution in the Infierno catchment as a whole.

7.8 Analysis and discussion of the quantitative landscape investigation in conjunction with field observations

The results of the landscape ecological investigation will be discussed as follows: individual subset level (Mocatán badlands, in the Mocatán catchment, Malaguica and Juan Contreras badlands in the Infierno catchment and the Sorbas subset in both catchments), catchment level (Infierno and Mocatán catchments) and study area level. By drawing together the FRAGSTATS and buffering results for each catchment and analysing them in conjunction with field observations a clearer understanding of the nature of the patterns of landcover can be achieved.

7.8.1 Mocatán badlands

This subset appears to have very small, fragmented patches of medium to dense vegetation (classes 3-6), and larger, contiguous areas of sparse cover (class1, surrounded by class 2). The sparsely vegetated areas which are related to erosional features (gullies, rills, pipes and depositional features) are found adjoining the densely vegetated areas. There is often no intermediately vegetated area between the two, and the cover goes from dense vegetation to bare and eroded surface in a short distance. This suggests that the erosion is directly intruding into the dense vegetation in this subset with no intermediate period in time or space between vegetated and non-vegetated, and that the environmental gradient between bare or sparsely vegetated cover and very densely vegetated cover is extremely steep. This pattern can be seen clearly in Figure 7.8 which shows the clustered NDVI image of the Mocatán badlands subset draped over the DEM.

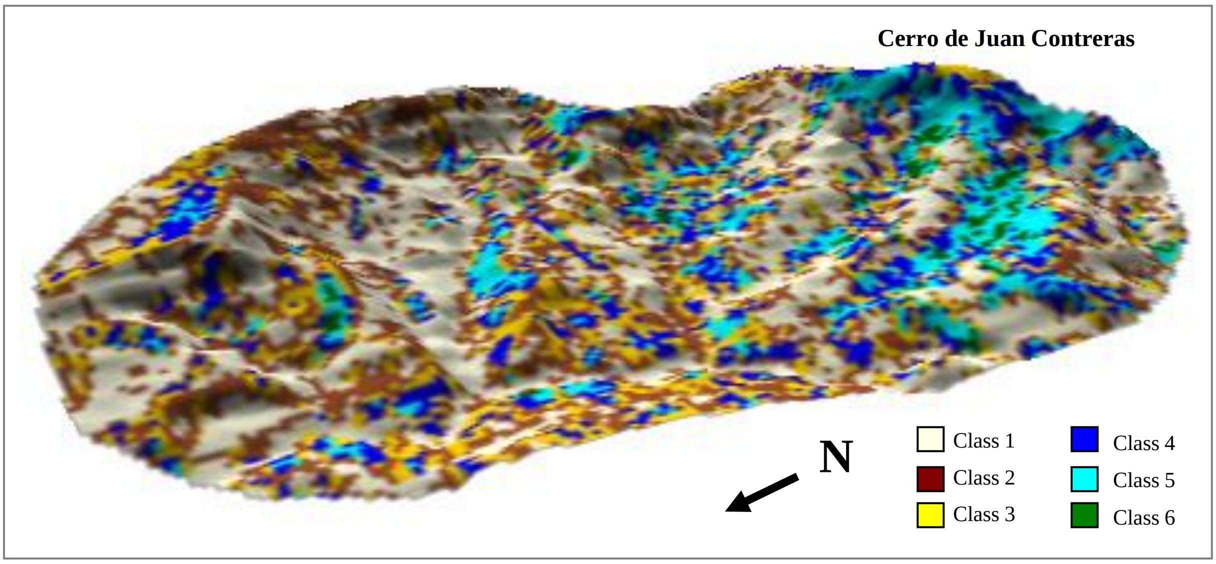


Figure 7.8 Clustered NDVI image of Mocatán badlands draped over the DEM

Observing this subset from a landscape ecological viewpoint, it seems very likely that class 1 comprises the matrix. Although class 1 does not quite comprise 50% of the total area, it is well connected along channels and is obviously aggressively cutting into the relict vegetation on Cerro de Juan Contreras. According to Forman's (1995) definition, the matrix needs to be more connected than the other elements in the landscape. Class 1 does appear to have the highest connectivity which is demonstrated in part by the results of the class buffering, and supported by the high nearest neighbour figures and high mean proximity index scores for this class. Another property of the matrix, control over dynamics (Forman, 1995), is generally thought to be difficult to assess, but it cannot be doubted that the erosion, which is driven by river-capture induced base-level change, must be the 'engine' which drives landscape change in this subset. That erosion is exerting control over the landscape dynamics is supported by the FRAGSTATS metric and the pixel adjacency scores. This subset has only small patches of dense vegetation and work here has shown that species richness is positively related to patch size (Alexander *et al*, 1999), so the denudation of vegetation cover by erosion appears to be reducing species diversity, at least locally. Forman's (1995) comments about a landscape composed only of small patches as being eviscerated are surely applicable in this subset.

7.8.2 Malaguica

Class 3 has the highest cover percentage in this subset, and also the largest average patch size, but has a very high patch size coefficient of variation indicating that the patch sizes in this class vary considerably. Class 3 cover is generally found on ridgetops and south facing ridge sides. Classes 5 and 6 which cover a lower percentage of this landscape have lower PSCV scores indicating less patch size variation. These two classes are generally found on agricultural terraces in the valley bottoms and class 5 is often found on north facing ridge sides. Class 4, occurring as small patches is scattered more widely through this subset than classes 5 and 6 and it has the highest patch density. Pixels of class 4 are most often self-adjacent or adjacent to class 3. Figure 7.9 shows the Malaguica subset draped over the DEM for that area demonstrating this pattern.

Examining the patterns of patches in this subset of the field area and the types of cover that the patches represent, cover of classes 2 and 3 has established itself extensively in areas where classes 5 and 6 are apparently unable to establish. These are areas with the greater moisture stress, south facing and ridge tops where soil depths tend to be more shallow. Cover of classes 5 and 6 is confined to the valley bottoms and north facing slopes of the ridges where the water-collecting capacity of the surviving agricultural terraces is more likely to facilitate establishment of dense vegetation. Class 5 cover is also well established on the shady northern sides of the ridges where the moisture stress is reduced due to aspect. This explanation of this pattern is supported by aspect figures (section 6.6.1.3) which indicate that sparse classes are strongly associated with south-west, south and south-east facing slopes whilst classes 5 and 6 are associated with north-east, north and north-west facing slopes. Class 4 appears to be more associated with class 3 than classes 5 and 6 (Table 7.5), and it is possible that this cover type exploits pockets of environmental resources within the main cover of class 3 where classes 5 and 6 are unable to establish.

It would appear then that the pattern of landcover in Malaguica has a fairly smooth environmental gradient between sparse and dense cover with dense classes 5 and 6 taking the flat valley bottoms and north facing slopes, class 4 providing a buffer between classes 5, and 3 and 2. However, as class 3 is the class with the highest percentage cover, it is obvious that this landscape has not got the opportunity to have as steep an environmental gradient as the Mocatán badlands as the large potential for a 5 class difference is not there in the landscape.

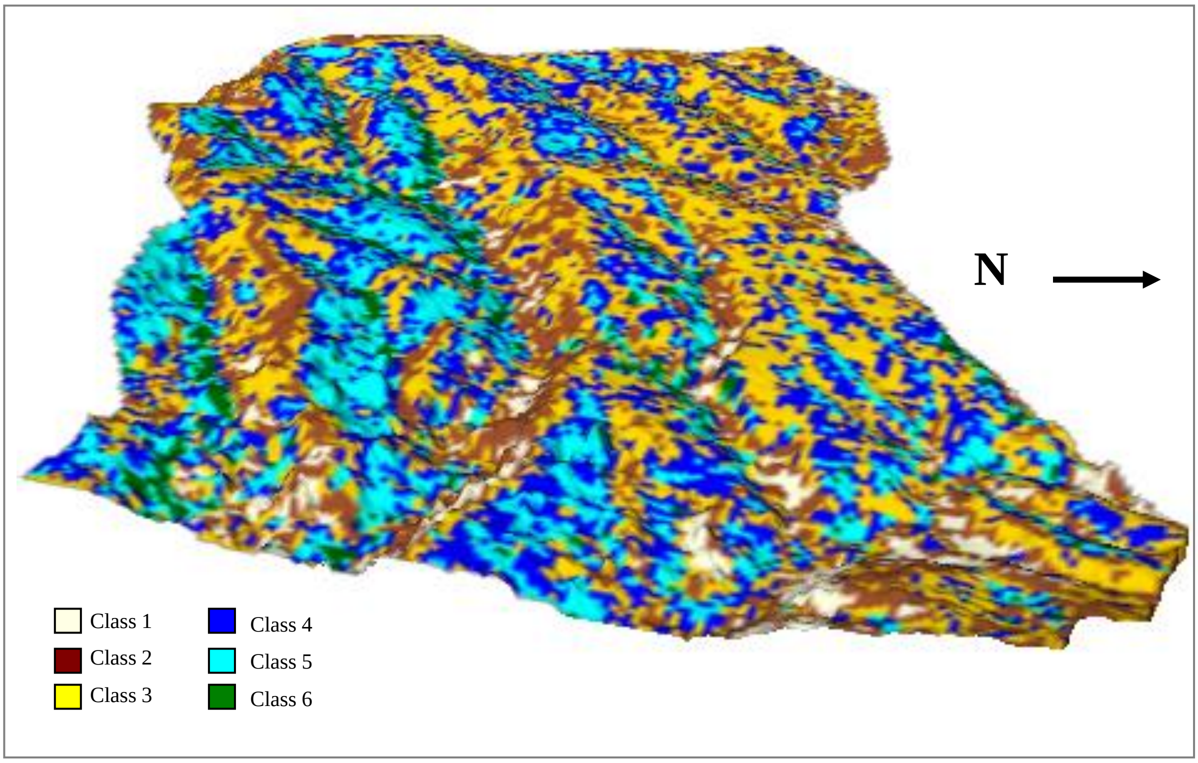


Figure 7.9 Clustered NDVI image of Malaguica draped over the DEM

It is difficult to identify a matrix class in this subset as none of the classes make up more than 32% of the total cover. Class 3 has the highest cover proportion and it is often self-adjacent, but it is hard to see how this class could be the control over dynamics in the subset when the cover distribution appears to be aspect and resource driven. Classes 5 and 6 are again highly associated with aspect, but it is also likely that other environmental variables are playing a part in their distribution (e.g. soil moisture and possibly soil depth and development which is likely to be greater in these valley bottoms). The driving force in this subset, if anything, is likely to be the post-terrace abandonment erosion taking place in the valley bottoms, which is evidenced by the presence of classes 1 and 2 in the agriculturally terraced areas. Much of this erosion is taking place as piping, or in narrow gullies and scars which may not be detected by the 5m resolution ATM data, so classes 1 and 2 are possibly under-represented. Malaguica is an area that appears to have stabilised after the river-capture base-level change had passed up the stream network. Cover then became distributed according to environmental resources. This pattern of landcover currently appears to be undergoing change due to localised disturbance in the channel bottoms. This change is picked up to some extent by the relatively small nearest neighbour distances for class 2 and the second highest MPI score for this class, along with a relatively high self adjacency score for a class which does not cover much of the subset. The change that this subset is undergoing may eventually cause gross overall changes to the cover distribution in this subset, or, as the channel reaches an equilibrium by removing the benches represented by the agricultural terraces and by regaining its former profile (Thompson and Scoging, 1995), the current wave of erosion may stabilise.

7.8.3 Juan Contreras badlands

The controls on the Juan Contreras badland subset appear to be erosion in the east and aspect in the west. In the east of the subset there is some evidence of relict vegetation on the sides of the hill into which the large badland area has been incised, which is similar to the behaviour of the Mocatán badlands around Cerro de Juan Contreras. In the west, a somewhat similar landcover pattern to that found in Malaguica can be identified, although patches of 4, 5 and 6 are more often interspersed with patches of 1, 2 and 3. Figure 7.10 shows this pattern of two different types of cover. The FRAGSTATS statistics indicate a mixed landcover pattern as they are giving a muted signal with no extremes. This indicates that the boundaries of this subset were perhaps not delineated around one particular cover pattern. It is likely that FRAGSTATS would have yielded a different set of figures if just the badland area or just the area to the west had been used. It is therefore difficult to use either the FRAGSTATS or buffering results in this subset to investigate what is happening in this landscape as the signals coming from the two different cover types appear to cancel each other out.

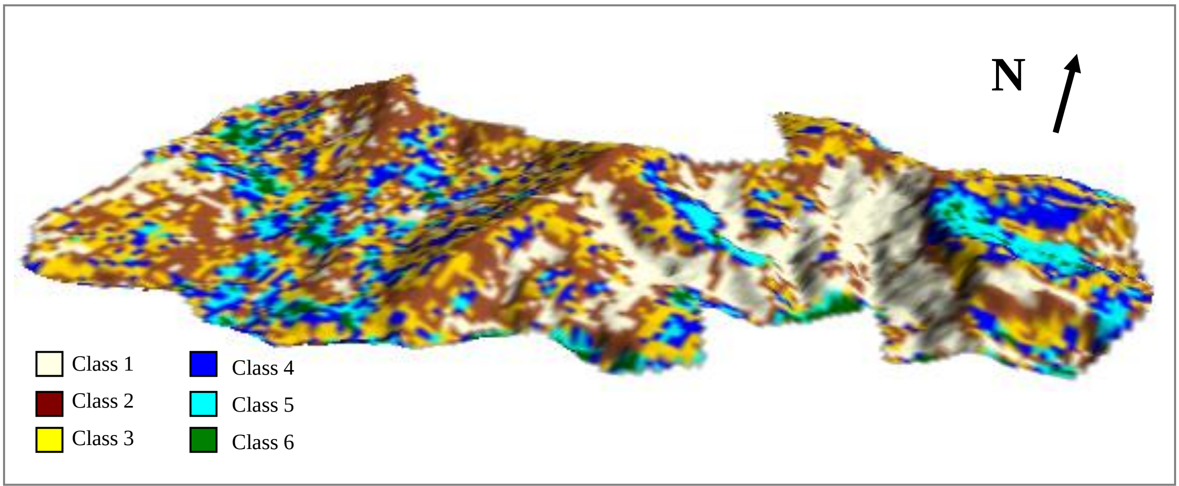


Figure 7.10 Clustered NDVI image of the Juan Contreras badlands draped over the DEM

7.8.4 Sorbas subset

The Sorbas subset is found across the south of both the Infierno and Mocatán catchments and is substantially different to the other three subsets. It is the only subset to have a class comprising 50% of the cover (class 5). It has the largest mean landscape patch size of all the subsets, at 0.07ha, and class 5 has a mean patch size of 0.25ha. Class 5 has the highest AWMSI in this subset (and highest of all the four subsets) indicating that this class has very irregular patch shapes. Class 5 is found mostly on hill tops and hill sides, it very often surrounds class 6 and is surrounded by class 4. This observation is supported by the class adjacency statistics (Table 7.5). The dense cover classes make up over 85% of this landscape (4, 5 and 6). The density of class 5 cover in this subset is shown in Figure 7.11.

The sparser classes (1, 2 and 3) are generally found in the channel bottoms and some areas of agricultural terraces. Aspect control does not appear to be much of an issue for class 5 as this class is ubiquitous on all slopes. However, classes 4 and 6 do appear to be associated with aspect; with class 6 being found in preference on east, north-east and north facing slopes and class 4 being found more often between south-east and south-west than would be expected (Table 6.11). Thus it appears that classes 6 and 4 are found within the 'blanket' cover of class 5 in areas which either have resources able to support more dense cover (class 6) or have environmental conditions which cannot support class 5 but are still able to support reasonably dense vegetation.

The matrix in this subset is quite obviously the dense vegetation represented by class 5. It comprises 50% of the landscape and has high levels of connectivity, which the MPI value supports. The large size of the patches of class 5 is likely to be a store for species with sufficient extent to contain core areas, possibly represented by class 6.

The Sorbas member underlying this area does not appear to have been affected by erosion to the same extent as the Gochar. The landcover here is very different to the cover patterns in the other three subsets which is reflected in the FRAGSTATS and buffering scores, hence more stable and resistant geology leads to more dense vegetation cover.

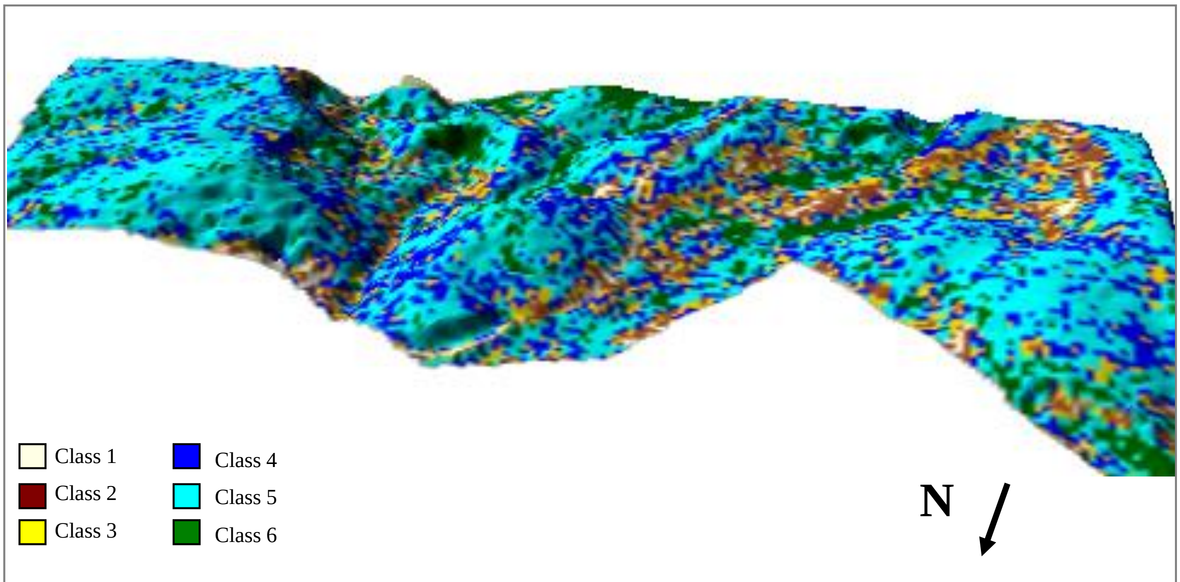


Figure 7.11 Clustered NDVI image of the Sorbas subset draped onto the DEM

7.8.5 Mocatán catchment

The Mocatán catchment has fairly sparse cover overall, with classes 1 and 2 comprising 57% of the landscape cover. There is a significant area of large, modern agricultural terraces in the north-west of the catchment which were bare when the remotely sensed data were acquired and which therefore increased the total cover of bare ground. In general the cover pattern in the Mocatán catchment is more 'noisy' than in the Infierno with more variation in patch size and patch distribution, and this is reflected in the FRAGSTATS values which show more extreme values than those for the Infierno catchment. Figure 7.12 shows the catchment clustered NDVI image draped over the DEM where this variation in patch size and distribution can be observed.

Class 1 is self adjacent 49% of the time which is partly a function of the large patches that comprise some of the class 1 cover, but is also a function of the connectivity of this class as opposed to the other classes in this catchment. The high connectivity is reflected in the extremely high MPI score for class 1 when compared to the scores for the other 5 classes (Table 7.2). AWMSI gives class 1 a high score indicating patch shape irregularity which is likely to be a function of the elongated patches of class 1 found in channels and on some ridges.

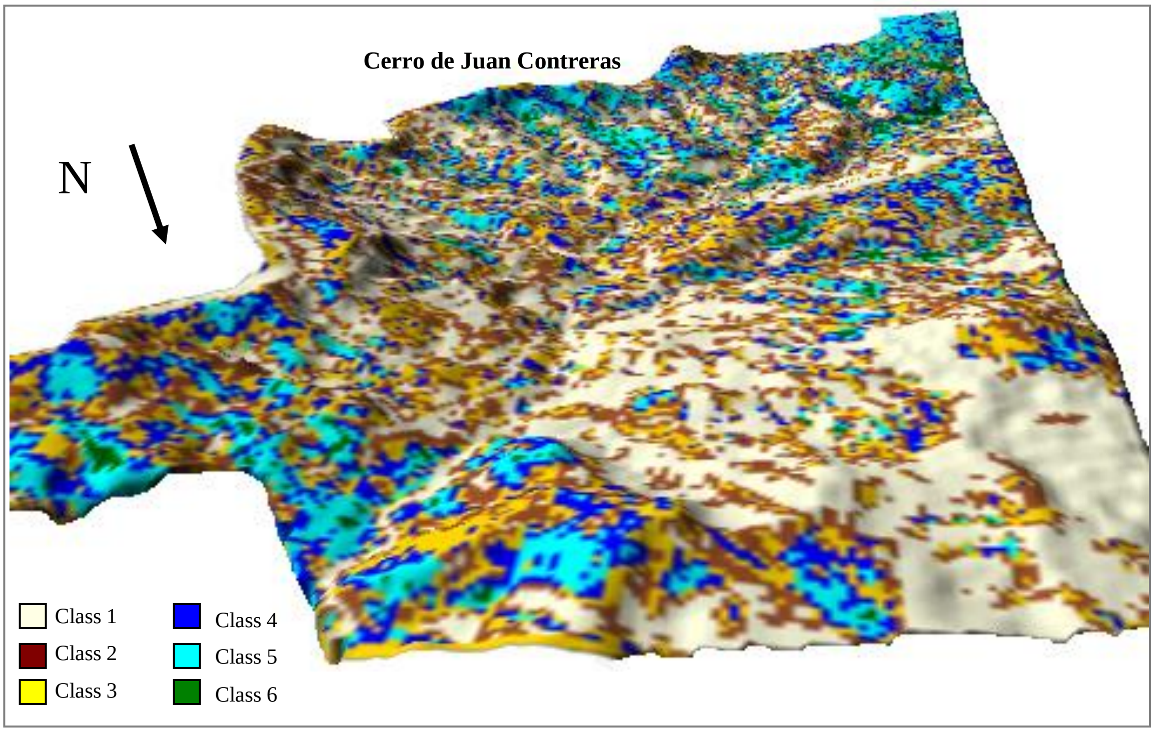


Figure 7.12 Clustered NDVI image of the Mocatán catchment draped over the DEM

The overall signal emerging from the Mocatán catchment is that class 1 is very important in the landscape. As with the Mocatán badlands section, it appears that class 1 is the matrix, and the erosion that it reflects is the driving force which is changing the form of the landscape. The dense cover classes (5 and 6) appear to be more associated with aspect than the sparse classes, an indication that class 1 is more ubiquitous in the landscape. This seems appropriate as the sparse vegetation or bare ground of class 1 is an indicator of erosion and generally occurs wherever surface erosion is found, including on the north-facing side of Cerro de Juan Contreras. The dense vegetation comprising classes 5 and 6 appears to be able to survive better on north-east, north and north-west facing slopes which could be an indicator of erosion having successfully removed this type of cover first from aspects which prove more inhospitable for dense vegetation. The patches of dense vegetation found on north facing hillsides, ridges and abandoned agricultural terraces within the channels are probably relics of the environment prior to the river-capture induced wave of erosion reaching this catchment. The nature of the dense plant cover on the hillside of Cerro de Juan Contreras is that of patches of vegetation that will not easily be recolonised if the areas become eroded. A survey of species versus patch size (Alexander *et al*, 1999) indicated that patches which were cut off from the main hillside vegetation on Cerro de Juan Contreras by erosion or human disturbance have lower numbers of species indicating progressive environmental degradation.

Some areas are degraded directly from class 5 to class 1; the juxtaposition of these two classes indicating a steep environmental gradient probably due to moisture stress. Other areas are suffering a more subtle form of degradation, for instance the type of class 4 which has a high proportion of standing shrub litter. These areas were once class 5 or 6, the litter being evidence that shrubs flourished in these areas. This type of degradation has been observed in areas where there is extensive piping through terraces; the pipes remove deep-rooting shrubs' access to ground water. The sequence of degradation is likely to follow a sequence where piping under dense cover induces moisture stress which instigates a change from class 5 cover to class 4. The pipes collapse inducing gullying, thus increasing moisture stress and erosion and classes 5 and 4 are degraded to classes 1 and 2.

7.8.6 Infierno catchment

The Infierno catchment appears in general to be less 'noisy' than the Mocatán catchment. There is not as large a variation in patch sizes or patch density as found in the Mocatán catchment. Patch shapes are less convoluted and MPI scores are much less extreme in variation indicating that no one class has very high connectivity, dividing the other classes up and so lowering their connectivity and thus their MPI scores.

The Infierno catchment pattern is influenced strongly by class 5 cover which lies in the south of the catchment on the Sorbas member. Class 3 in the north-east of the catchment (Malaguica area) does appear to have some effect on the overall pattern of FRAGSTATS scores for the catchment, as its MPI score is also quite high. Cover patterns are very obvious in Figure 7.13. Classes 1 and 2 appear to play very little part in the overall pattern of cover in the Infierno catchment, and as the presence of these cover classes is an analogue for erosion, it would appear that the Infierno catchment, overall is currently undergoing less erosion than the Mocatán catchment.

It seems that the Infierno catchment has a well defined matrix in the south and a less well defined matrix in the north. The area which includes the Sorbas subset on the Sorbas member definitely has class 5 as the matrix, as defined in 7.8.4, with the same patterns of class 6 being found within class 5, and class 5 in turn within class 4. However, this pattern does not hold in the north of the catchment, as it changes at the Sorbas/Gochar lithology boundary (approximately along the line A-B in Figure 7.11). As discussed in section 7.8.2, the distribution of cover in the northern section of the catchment is strongly associated with aspect, and in this section of the catchment, there may not be a cover class which acts as the matrix. In other areas, different landcover classes may act as matrix. For example, the re-establishment of the drainage pattern through terrace degradation in the Barranco del Infierno may be the matrix at that location. In the middle of the catchment on the Barranco de los Contreras, the large badland area is likely to be driving landscape change in that section, as remnant landcover is eroded and replaced by class 1.

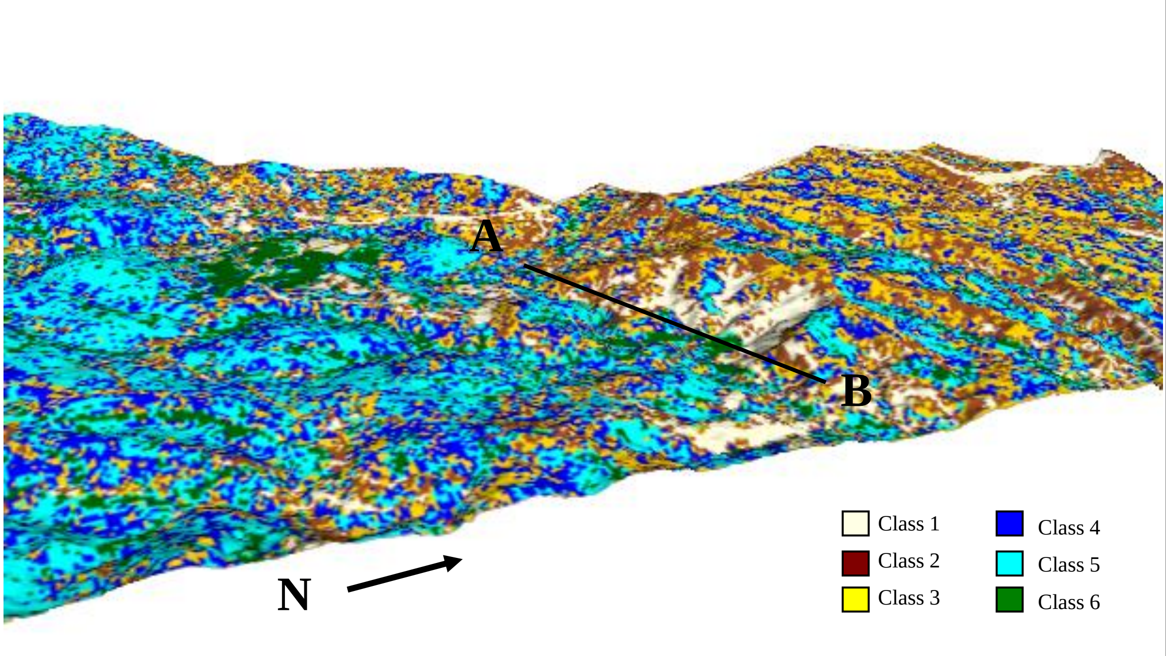


Figure 7.13 Clustered NDVI image of the Infierno catchment draped over the DEM

7.9 Summary

Overall the Infierno catchment is composed of at least three different landcover patterns which when analysed together using FRAGSTATS have resulted in the output of moderate landscape metrics. The Mocatán catchment however, is almost entirely composed of a pattern where class 1, and the erosion which it reflects is the dominant landcover type and results in more extreme landscape metric scores. The catchment level statistics for Mocatán reflect the subset level statistics for the Mocatán badlands, whereas the Infierno statistics do not really reflect those of Malaguica. The statistics output by FRAGSTATS for the Infierno catchment are muted in comparison to those statistics gathered for the Sorbas and Malaguica subsets, and reflect more the output for the Juan Contreras badlands which itself was a mixed subset. FRAGSTATS has been useful in producing a quantitative description of landcover patterns in the Mocatán badlands, Malaguica and Sorbas subsets, and the Mocatán catchment overall. This demonstrates the importance of careful delineation of subset boundaries when investigating landcover patterns. If an area appears to contain mixed landcover patterns, then it does not appear that FRAGSTATS reveals very much useful information about the landscape being investigated, as has been the case with Juan Contreras badlands and the Infierno catchment subsets.

8 CONTROLS ON LANDCOVER PATTERNS IN TWO CONTRASTING CATCHMENTS: A DISCUSSION

8.1 Introduction

Results of the vegetation analyses, aspect, slope and wetness analyses by NDVI class and landscape ecological examination of the cover patterns were presented in Chapters 3, 6 and 7 respectively. This chapter draws together the results of these investigations in order to assess the relative importance of controlling landcover patterns in the two catchments.

8.2 Assessing the likely controls on landcover pattern

Table 8.1 shows an assessment of the factors affecting distribution of cover density, cover type and species, which has been compiled using the results of the analyses reported in Chapters 3, 6 and 7 together with observations made in the field. Cover density is the amount of green vegetation as defined by the clustered NDVI image. Cover type is the physiognomic cover as collected during field survey and species type is the floristic data collected at the same time. The likely controls on the distribution of cover density have been determined by analyses of the slope, aspect and wetness statistics and by investigation of landcover pattern using FRAGSTATS. Controls on the distribution of cover type and species type have been determined by examining DECORANA and TWINSPAN output in the light of environmental variables measured in the field.

	Geology	**Geomorphology/ catchment**	**Aspect**	**Slope**	**Wetness**	**Soil chemistry**
Scale	Coarse	Medium Coarse	Medium	Medium	Medium	Fine
Cover density	5	3	3	2	1	2
Cover type	5	4	2	1	n/a	4
Species type	5	4	1	2	n/a	3

Table 8.1 Relative importance of controls on cover patterns in the study area (1 is weakest 5 is strongest control)

8.2.1 Cover density controls

If pattern is correlated to process (Gustafson 1998), the cover density patterns in the study area are telling a story of their recent geomorphological history underlain at all times by geology. The most likely control on cover density patterns at a coarse scale is geology. This must account for the gross differences in cover with Malaguica type cover found on MRU, Mocatán badlands type cover found on TRU and the fairly continuous cover of much denser vegetation found on the Sorbas member. The most striking example of geology controlling cover pattern is the cover found on the Sorbas member. The low hills in the south of the study area have been deeply incised in the Infierno catchment and yet cover densities are similar to those found in the south of the Mocatán catchment where the incision has not reached as great a depth. The common factor in these two areas is that they are both on the Sorbas member has proved to be more resistant than the Gochar, to the waves of incision from the river capture. Therefore geology is likely to be a controlling factor at the coarse scale in this area.

Geology is not the only control on cover density. Geomorphology, or catchment, is also important at a medium coarse scale. The cover densities vary between areas of the same geology but in different catchments. A prime example of this is the cover found on the south-east facing side of Cerro de Juan Contreras down to the Barranco de los Contreras. This side of the ridge drains into the Infierno catchment but is still on the TRU, thus was exposed to the much earlier wave of incision of the Infierno catchment. When the cover patterns of this area are compared to cover patterns on TRU in the Mocatán catchment they are very different, the most striking difference being the almost complete lack of bare class 1 type cover and the predominance of classes 3, 4 and even 5. An area facing in this direction in the Mocatán catchment would be expected to have much more classes 1 and 2. The cover pattern here is more akin to that found on the MRU in Malaguica indicating that this area has stabilised to some extent allowing colonisation of steep, south-east facing slopes which would be unlikely to colonise whilst very active erosion was taking place.

Aspect appears to be a strong control on cover density pattern at a medium scale. In both the catchments and all four subsets within the catchments, aspect is strongly associated with cover density, the more dense cover types being found more often on north facing slopes, and sparse cover on south facing slopes. The only area where aspect does not appear to be a very strong control is on the Sorbas member. Slope and soil wetness appear to be weaker controls on cover density across the field area, although their relationship with cover density is found to be significant using Chi Square.

There does appear to be some relationship between soil chemistry and cover density. There is a reduction in conductivity and sodium levels and an increase in calcium levels with increasing cover density (see Appendix 5 for boxplots of soil chemistry and NDVI class). However, the sample size is small when compared to the use of all 5m pixels across the study area for aspect, slope and wetness investigations; and thus more investigation of this relationship is needed.

8.2.2 Cover type controls

NDVI does not discriminate directly between cover types, but shows only the amount of green vegetation present, although relationships could be established between NDVI class and combinations of structural cover elements (Chapter 6). The cover investigations carried out during the 1997 and 1998 field survey provide more detailed information about what types of cover are extant throughout the study area. The association between cover type and environmental variables was assessed in

Chapter 3 using TWINSPAN and DECORANA. The results indicate that geology exerts slightly less control on cover type than on cover density, but that catchment is more strongly related to cover type distribution than it is to cover density. Cover type also appears to be controlled by soil chemistry with high levels of exchangeable cations being associated with area of similar cover type with bare silt crust and small shrubs and low levels being associated with areas with high percentages of tall shrubs.

Aspect appears to exert moderate control on cover type distribution in the study area. This is because what is being measured is not density but type of cover. On north-facing slopes there is generally more cover but not necessarily of a different type to that found on south-facing slopes; for example, clump grass is found in training areas facing all directions, but comes in different cover densities depending on the aspect. Slope does not appear to have a very strong relationship with separation of cover types.

8.2.3 Controls on species type

It appears from the DECORANA results (Chapter 3) that catchment exerts a strong control on the distribution of species. Catchment is an analogue for the geomorphological change that has taken place due to the wave of incision that worked up the Infierno catchment, which then stabilised, and the current incision taking place in the Mocatán catchment. The differences in the catchments due to their different erosional histories includes soil removal from hillsides and the catchments also represent corridors for the movement of species. Parts of the Mocatán catchment have different species compared to parts of the Infierno catchment, with some of these differences occurring just across the watershed. For example, dense vegetation dominated by *Anthyllis spp.* and *Thymelea hirsuta* is found in the Mocatán catchment high up on the side of Cerro de Juan Contreras and on the other side of the watershed in the Infierno catchment on a slope facing in the same direction is found a community dominated by *Ulex parviflora* and *Cistus spp*. The north side of Cerro de Juan Contreras supports a much more diverse range of plant species than the north facing slopes in the Malaguica section of the Infierno catchment.

However, the differences in species between the two catchments are found mainly on the Gochar material. There appears to be little difference between species on the Sorbas member in the two catchments. As the Gochar material (both TRU and MRU) is very susceptible to erosion, the effects of the wave of incision are highlighted here in the species difference. Once again, therefore, the gross overall control is probably the geology, as the species distribution on the Sorbas is very similar across both catchments indicating that this area has not suffered the same removal of soil as the Gochar material.

Soil chemistry has some bearing on species distribution in the catchments where high exchangeable cation levels are associated with species found in the most degraded types of sites (for example *Limonium insigne* and *Lygeum spartum*) and sites with low levels of exchangeable cations are generally the most stable sites associated with species such as *Ulex parviflora*, *Cistus albidus* and

Siderites spp. Slope has a weak association with distribution of species in the training areas sampled and aspect appears to have very little control on the distribution of species. This may seem counter-intuitive, but most species were found in training areas facing in all directions. It is the density of plant cover rather than the actual species present that appears to be affected by aspect.

8.3 Summary

It is hypothesised that both catchments originally had a relatively dense cover of vegetation somewhat similar to that found today on the Sorbas member and on areas of the Gochar unaffected by the current wave of erosion (e.g. the north-facing upper slopes of Cerro de Juan Contreras). The wave of incision which removed Gochar material from the Infierno catchment also removed its ability to support both high densities of vegetation cover and certain plant species high up on hillsides. In the Mocatán catchment, it is still possible to see patches of the types of dense vegetation cover on the Gochar that would once have been found across the catchment in a similar way to the dense cover currently found on the Sorbas member. However, this plant community is now experiencing stress due to the wave of erosion which has reached the Mocatán catchment and is currently removing sediment from the hillsides. The plant communities are being degraded by the erosion and are likely to disappear from the Gochar in the Mocatán catchment.

In the Malaguica area of the Infierno catchment, recolonisation by dense vegetation has taken place on the valley floors and lower hillsides. It is likely that this recolonisation has been aided by the agricultural terracing in the valley bottoms. However, the higher hillsides have not been colonised with the same plant species or to the same extent as the north facing hillsides of similar type in the Mocatán catchment, where the relict plant cover is more dense and the species types more varied.

A possible scenario is that the Malaguica section of the Infierno catchment shows how the patterns of landcover in the Mocatán catchment will look in the future after the wave of incision has passed through. Once the catchment has restabilised, plants will recolonise via the stream channels. However, the potential for the landscape to support the wide variety of plant species that are currently found in areas of the Mocatán catchment is likely to be compromised. The densest cover will be found in the channels and on the low slopes, but the dense cover currently found higher up on some hillsides will not be able to recover due to soil loss. Cover on the Sorbas member will probably not change much. The above scenario is what may happen if the Mocatán catchment is left alone. However, it is probable that human intervention will occur in this catchment as it is already extensively used for agriculture downstream of the study area, and this will change the cover patterns of the landscape more radically and much faster than would happen if the course of events were left to happen naturally.

9 CONCLUSIONS

9.1 Achievement of aims

If, as Gustafson (1998) states, there is a correlation between ecological pattern and ecological process, then by investigating pattern, the controlling processes should become apparent, The aims of this thesis were to investigate the relationships between environmental variables and landcover pattern by using landscape ecology techniques, and thus identify the major controls on landcover pattern in two adjacent catchments; and to assess the utility of a landscape ecological approach for investigating vegetation cover pattern in a semi-arid area.

The aims of the thesis have been achieved in the following ways

a. Field survey and remotely sensed data have been integrated to produce a map of cover density across the study area.

b. Field survey and vegetation analysis techniques have been used to identify the distribution of cover and species type across the study area.

c. Detailed analysis of the relationships between cover density and aspect, slope and wetness have been carried out.

d. Landscape ecological analysis has been carried out using the cover density map to investigate the pattern of cover.

e. Relationships between cover pattern and environmental variables have been identified and ranked in order of likelihood of control.

9.2 Major conclusions

Geology is the major control on the landcover density pattern in the study area at the coarse scale. Geomorphological history and aspect are also strong contributing factors to cover density pattern at the medium scale. Slope and wetness are controlling factors only in localised areas.

Geology is the major control on cover and species type distribution in the study area. Geomorphological history and soil chemistry also play a part in cover and species type distribution. Aspect and slope are less important controls on the cover and species type distribution.

The Mocatán catchment would probably come to have a similar landcover pattern to that of the northern section of the Infierno catchment after the wave of erosion has passed through, and the catchment has stabilised. However, it is likely that human activity taking place in the catchment will not allow a natural stabilisation and recolonisation by vegetation to take place.

Landscape ecological analysis in general, and FRAGSTATS in particular have been shown to be suitable tools for the investigation of landcover in a semi-arid area, providing that areas with similar cover patterns are analysed separately to prevent loss of the signal from the cover pattern.

9.3 Recommendations for further work

A finer scale analysis of environmental variables at the patch level is now needed. The work reported in this thesis looked at the broad, catchment scale processes. To begin to build up a picture of processes taking place at patch level, small areas comprising just a few patches should be chosen in the two catchments and a thorough investigation of soil chemistry, soil moisture, erosional feature and their relation to species composition needs to be conducted. This could then be related to FRAGSTATS output for the individual patches so that the patch level relationships between environmental variables and cover pattern can be investigated.

A comparison of the 1996 NERC ATM data with ATM data acquired by NERC in April 2001 should be undertaken to investigate vegetation change over the past 5 years. Of particular interest would be whether the Malaguica area is losing plant cover due to the reconnection of the agricultural terraces with the drainage network, and the extent to which erosion, and thus vegetation loss, has taken place in the Mocatán catchment since 1996.

The application of these landscape ecological techniques to another semi-arid area with a similar landscape should be carried out to see whether it would be possible to identify the gross overall controls on the landcover pattern using FRAGSTATS with a clustered NDVI image. It should be investigated whether landscapes undergoing similar levels of disturbance to those found in the study area give similar results.

APPENDIX 1

SPECIES RECORDED IN 1997, 1998 AND 2000 TRAINING AREAS

Table A1.1 below shows species recorded in each training area

TA_number	Aegilops geniculata	Agrostis spp.	Alyssum spp	Anabasis articulata	Anagallis spp	Annual types	Anthyllis spp	Artemisia spp.	Asparagus stipularis	Asphodelus fistulas	Astragalus monspessulanus	Atractylis humilis	Avena hirtula	Bellis spp.	Brachypodium retusum	Bromus rudens	Bupleurum spp.	Calendula spp	Capsella bursa-pastoris	Carrichera annua vesicaria	Cistanche phelypaea	Cistus albedus	Cistus lavendufolia	Cistus libanotis	Compositae spp	Convolvulus althaeoides	Coris monospeliensis	Coronilla juncea	Crassula spp.	Crucifer sp	Cuscuta epithymum	Dactylis glomerata	Daphne gnidium
1	0	0	0	0	0	0	3	0	0	0	3	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
2	0	0	0	0	0	0	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	4	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
4	0	0	0	0	2	2	5	1	0	0	3	0	0	0	2	0	0	0	0	0	0	0	0	1	2	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0
6	0	0	0	2	0	0	3	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
7	2	0	0	0	0	0	6	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	1	0	0	0	0	0	0	0	0
8	0	0	0	0	0	3	3	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	2	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	2	4	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	2	0
11	2	0	0	0	0	0	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0
12	0	0	0	0	0	3	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	2	0	0	2	0	0	0	2	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	2	2	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	3	2	0	0	2	0	0	0	0	0	0	1	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0
23	0	0	0	0	2	0	2	3	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	3	1	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	2	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
25	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0
26	0	0	0	0	0	0	2	0	1	0	2	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0
27	0	0	0	0	0	2	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	2	0
28	0	0	0	0	0	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0
29	0	0	0	0	0	0	3	0	0	0	0	0	3	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
31	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0
32	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
33	0	0	0	0	0	0	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0
34	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	1	1	0	0	0	0	0	0	0
35	0	0	0	0	2	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	2	0
36	0	0	0	0	2	0	3	2	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	2	0
37	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0
38	0	0	0	0	2	2	5	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	2	0	0	0	0	0	0	3	0
39	0	0	0	0	0	0	2	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0
40	0	0	0	0	0	0	3	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0
41	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0
42	0	0	0	0	2	0	3	2	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	4	2	0	0	0	0	0	0	3	0
43	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0
44	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0
45	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	1	0	0
46	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0
47	0	0	0	0	0	0	0	0	2	0	0	0	0	0	5	0	0	0	0	0	0	0	0	3	1	0	0	3	0	0	0	0	0
48	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	2	0	0	0	0	0	0
49	0	0	0	0	0	0	1	2	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	2	0	0	0	0	0	0	1	0	0
50	0	0	0	0	0	1	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	1	0	0	0	0	0	0	0
51	0	0	0	0	0	0	0	2	1	0	0	0	0	0	5	0	0	0	0	0	0	0	0	2	2	0	0	0	0	1	0	0	0
52	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0	3	0	3	0	0	0	0	0	0	0	0	0
53	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	2	0	0	0	2	0	0
54	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	1	2	0	0	0	0	0	0
55	0	0	0	0	0	2	0	2	0	0	0	0	0	0	3	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
56	3	0	0	0	0	1	0	1	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	2	2	2	0	0	0	0	0	0	0
57	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	2	0	0	0	0	0	0
58	0	0	0	0	0	0	0	2	1	2	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0
59	0	0	0	0	0	0	2	0	2	0	0	0	0	0	0	0	0	0	0	0	0	3	0	3	0	0	0	0	0	0	0	0	0
60	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	0	0	0	0	0	0	0	0	0
61	0	0	0	0	0	0	2	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0
62	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0
63	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	2	0	5	0	0	0	0	0	0	0	0	0
64	0	0	0	0	0	0	3	2	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0
65	0	0	0	0	0	0	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	4	0	0	0	2	0	0	0	0	0
66	0	0	0	0	0	0	4	1	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0
67	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
68	0	1	0	1	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0
69	0	1	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
70	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
71	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	2	0	0	0	0	0	0	0	0	0
72	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
73	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
74	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	0	0	0	0	0	0	0	0	0
75	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0
76	0	0	0	2	2	0	0	0	0	0	0	0	1	0	0	4	0	0	0	0	0	0	2	2	0	0	2	0	0	0	0	0	0
77	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	2	2	2	0	0	0	0	0	0	0	0	0
78	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	4	0	0	2	5	0	0	0	0	0	0	0	0	0
79	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	2	0	0	0	5	0	0	0	0	0	0	0	0	0
80	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	3	0	0	0	3	0	0	0	4	0	0	0	0	0	0	0	0	0
81	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0
82	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0
83	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	3	0	0	0	0	0	0	0	0	0
84	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	1	2	4	0	0	0	0	0	0	0	0	0
85	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	3	0	0	0	0	1	0	0	0	0	0
86	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0
87	0	1	0	0	0	0	3	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
88	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0
89	0	2	0	1	0	0	0	0	0	0	0	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
90	1	0	0	2	0	0	0	0	0	1	0	0	2	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
91	0	1	0	0	0	0	3	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
92	0	0	0	0	0	0	2	0	0	0	0	0	0	0	1	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
93	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
94	0	1	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
95	0	2	0	1	0	0	0	0	0	0	0	0	2	0	0	4	0	0	0	2	0	0	2	0	0	0	0	0	0	0	0	0	0
96	0	0	0	1	0	0	0	0	0	2	0	1	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	1	0	2	0	0
97	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
98	0	2	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
99	0	0	0	2	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	1	0	0	0	0	0
100	0	1	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	2	0	0	0	0	0	0	0	0	0	0
101	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	2	0	0	0	0	0	0	0	0	0	0
102	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	2	0	0	0	1	0	0	0	0	0	0
103	0	0	0	1	1	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0
104	0	0	0	1	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	2	0	0	0	0	0	0
105	0	0	0	1	0	0	3	0	0	0	1	0	0	0	0	2	0	0	0	1	0	0	1	0	0	1	0	0	0	0	0	0	0
106	0	0	0	1	0	0	2	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	1	0	0	1	0	0	0	0	0	0
107	0	1	0	1	0	0	2	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
108	0	2	0	0	0	0	3	0	0	0	0	1	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
109	0	0	0	0	0	1	2	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
110	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table A1.1 Species data collected in the field by training areas

TA_number	Phlomis lychnitis	Phlomis purpurea	Pistacea lentiscus	Plantago spp	Polygala rupestris	Prunus dulcis	Pulicaria odora	Reseda lutea	Rhamnus lycioides	Rosemarinus officinalis	Salsola genistoides	Salsola spp	Salvea verbenaca	Scabiosa monspellensis	Scandix pecten-veneris	Scorpuriuvus muricatus	Scorzonera graminaefolia	Sedum sediforme	Siderites spp.	Silene spp	Spartium junceum	Stipa parviflora	Stipa tenacissima	Teucrium polium	Teucrium pseudochamaepit	Thistle spp	Thymelea hirsuta	Thymus spp	Ulex parviflorus	Valentia hispeda
1	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0
2	0	0	0	0	0	0	0	0	0	1	2	0	0	0	0	0	0	0	2	0	0	0	1	0	0	0	1	2	1	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	1	0	1	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	4	0	0
5	0	0	0	0	0	0	0	0	0	2	1	0	0	0	0	0	0	2	0	0	0	0	2	0	0	0	2	3	0	0
6	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	2	0	0	0	0	1	0	0	0	0	2	0	0
7	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	4	3	0	0
8	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0
9	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	2	0	0	0	0	0	0	0	2	1	2	0	0
11	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	3	4	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	3	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	2	2	0	0
14	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	1	0	0	1	2	0	0	0
15	0	0	0	0	0	0	2	0	0	0	3	0	0	0	0	0	0	2	0	0	0	2	0	0	0	0	1	3	0	0
16	2	3	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0
17	0	0	0	0	0	0	0	0	0	1	3	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	3	2	0	0
18	0	0	0	0	0	0	0	0	0	1	4	0	0	0	0	0	0	0	1	0	0	2	0	0	0	0	2	3	0	0
19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	2	0	0
20	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	3	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	2	0	0	0	1	2	3	0	0
23	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	2	3	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	1	0	0	0	0	0	2	0	0
25	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	2	0	0
26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	2	2	0	0	0
27	0	0	0	0	0	0	0	0	0	1	2	0	0	0	0	0	0	2	0	0	0	2	0	0	0	0	0	2	0	0
28	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	2	1	0	0	0	0	0	0	0
29	0	0	0	0	0	0	1	0	0	0	3	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0
30	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	2	0	0	0	0	1	0	0	0	0	0	0	0
31	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	4	0	0	0	2	2	0	0
32	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0
33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	2	0	0
34	0	0	0	0	0	0	0	0	0	1	3	0	0	0	0	0	0	2	0	0	0	2	2	0	0	0	3	4	0	0
35	0	2	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	3	0	0	1	3	0	0	0	0	0	3	0	0
36	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	2	0	0	0	2	2	0	0	2	0	2	0	0
37	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	2	0	0	0	0	4	0	0	0	2	2	2	0
38	0	0	0	0	0	0	1	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	4	0	0
39	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	4	0	0	0	0	3	2	0
40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	4	0	0	0	0	3	0	0
41	0	2	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	2	0	0	0	0	2	0	0	0	2	0	0	0
42	2	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0
43	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	1	0	0	0	3	2	5	0
44	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	3	0	3	0
45	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	2	0	0	0	2	0	0	0	2	2	2	0
46	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	4	0	1	0	3	2	4	0
47	0	0	0	0	0	0	0	0	3	1	0	0	0	0	0	0	0	0	2	0	0	0	2	0	0	0	3	2	2	0
48	0	0	0	0	0	0	0	0	0	2	2	0	0	0	0	0	0	0	0	0	0	0	3	1	2	0	2	2	0	0
49	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	1	2	0	0	0	1	2	0	0	3	2	0	0
50	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	2	0	1	0	2	0	1	0
51	0	0	0	0	0	0	0	1	0	0	2	0	2	0	0	0	0	2	0	0	0	3	0	0	2	0	3	3	2	0
52	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	2	0	0	0	2	0	0	1	3	2	4	0
53	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	3	0	0	0	2	3	4	0
54	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	1	0	0	2	1	0	0	0	3	3	1	0
55	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	2	1	0	2	1	3	0	0	0
56	1	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	1	2	0	1	1	0	0	0	1	1	2	1	0
57	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	5	0	0	0	2	2	2	0
58	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	2	0	5	0	0	2	0	2	0	0
59	0	0	2	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	2	0	0	1	0	0	3	0
60	0	0	0	0	0	0	0	0	2	0	3	0	0	0	0	0	0	2	0	0	0	0	2	0	0	0	2	2	0	0
61	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	2	0	0	0	0	4	0	0	0	0	0	3	0
62	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	2	0	0	0	0	4	0	0	0	0	2	0	0
63	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	3	0
64	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	2	1	3	3	0
65	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	2	0
66	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	1	0	0	0	1	0	0	0	1	0	1	0	0
67	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	1	0	0	0	0	2	0	0	0	0	2	0	0
68	0	0	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	4	0	0
69	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	1	0	1	0	1	0	4	0	0
70	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	3	0	0	1	0	2	0	0
71	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	1	0	0	0	0	3	0	0	0	0	1	0	0
72	0	0	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0
73	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	3	0	0	0	2	0	0	0	0	0	0	0	0
74	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	1	0	2	0	0
75	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	2	0	0	0	0	3	0	0	0	0	5	0	0
76	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	3	0	0	0
77	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
78	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	2	0	0	0	0	0
79	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0
80	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0
81	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	1	0	0	0	0	1	0	0	1	0	2	0	0
82	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0
83	0	0	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0
84	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0
85	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3	0	0
86	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	3	0	0
87	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	2	1	4	0
88	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	2	0	0	0
89	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	3	2	6	0
90	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	3	0	0
91	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	3	0	0	0
92	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0
93	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	6	0	0	0	0	0	0	0
94	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	1	3	5	0	0
95	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	2	0	0	0	0	0	0	0	0	5	0	0
96	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	4	3	0
97	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	1	0	0	0	0	2	0
98	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	1	0	0	0	1	4	0
99	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0
100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	3	0	0
101	2	0	0	0	0	0	0	0	0	0	3	0	0	1	0	0	2	0	0	1	0	0	0	0	0	0	0	1	0	1
102	0	0	0	0	1	0	0	0	0	0	2	0	0	0	0	0	0	1	0	0	0	0	0	0	0	2	0	4	2	1
103	0	0	0	1	0	0	0	0	0	0	3	0	0	0	0	0	1	2	0	0	0	0	0	0	0	0	2	4	0	0
104	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	2	3	0	1
105	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	3	0	0
106	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	2	0	0
107	0	1	0	0	2	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	4	3	0
108	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	1	0	2	0	0	0	0	0	2	0	3	3	4	0
109	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	2	0	0	0	4	1	0	0	2	2	1	0
110	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	2	0	1	0	0	1	0	0

Table A1.1 continued

TA_number	Erodium petraeum	Eryngium spp	Eumozodendron bourgaeanum	Euphorbia spp.	Ferula communis	Frankenia thymefolia	Fumana ericoides	Gallium spp	Gladiolus illryicus	Grass spp	Hedysarum spinosissimum	Helianthumum spp	Helichrysum italicum	Hippocrepis glauca	Hippocrepis unisiliquosa	Hordeum spp	Junceum spp	Lathyrus spp.	Launea spinosa	Leguminosae spp	Lichen spp	Limonium insigne	Linum spp	Lygeum spartum	Lygos sphaerocarpa	Malcomia africana	Medicago sp	Moricandia arvensis	Muscari comosum	Myosotis sp.	Nerium oleander	Nigella damascena	Olea europea
1	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	1	0	0	0	0	2	0	0	0	0	0	1	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	2	0	0	0	0	2	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	2	1	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	2	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	4	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	3	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	3	0	0	2	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	2	0	3	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0	2	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	2	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
16	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17	0	1	0	0	0	0	1	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
18	0	0	0	0	0	0	1	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	2	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	2	0	0	0	0	0	1	0	0	0	0	0	0	0	2	2	0	3	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	2	0	0	3	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	3	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	2	0	4	0	0	0	0	0	0	0	0	0
25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	3	1	0	0	0	0	0	0	0	0
26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0
28	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	2	0	3	0	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	1	0	0	0	0	1
31	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	2	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0
32	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	2	0	3	0	0	0	0	0	0	0	0	0
33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	1	0	3	0	0	0	0	0	0	0	0	0
34	0	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
35	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
36	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	2	0	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
37	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
38	0	0	0	0	0	0	1	0	0	0	0	0	2	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
39	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0
40	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0
41	0	2	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	2	0	2	0	0	0	0	0	0	0	0	0	0	0	0
42	0	0	0	0	2	0	1	0	0	0	0	0	2	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
43	0	0	0	1	0	0	2	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
44	0	1	0	1	0	0	2	0	0	0	0	0	1	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
45	0	1	0	1	0	0	2	0	0	0	0	0	3	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
46	0	0	0	0	0	0	2	0	0	0	0	0	2	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
47	0	1	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
48	0	1	0	1	0	0	2	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
49	0	2	0	2	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
50	0	0	0	0	0	0	2	0	0	0	0	0	2	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
51	0	2	0	2	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	0	0	0
52	0	0	0	3	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
53	0	2	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	2	0	2	0	0	0	0	0	0	0	0	0	0	0	0
54	0	1	0	2	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
55	0	1	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
56	0	1	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
57	0	0	0	0	0	0	2	0	0	0	0	0	2	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
58	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
59	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
60	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
61	0	1	0	0	0	0	3	0	0	0	0	0	2	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0
62	0	0	0	0	0	0	2	0	0	0	0	0	1	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0
63	0	1	0	0	0	0	2	0	0	0	0	0	1	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0
64	0	1	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0
65	0	0	0	0	0	0	2	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
66	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
67	0	0	0	0	1	1	4	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0
68	0	0	0	0	2	1	0	1	2	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	2	1	0	0	0	0	0	2	0
69	0	0	0	1	0	0	3	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
70	0	0	0	0	1	0	3	1	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
71	0	0	0	0	1	0	2	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
72	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	1	0	0	0	0	2	0	2	0
73	2	0	0	0	0	3	4	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	2	0	0	0	0	0	0	0	0
74	1	0	0	2	0	0	4	2	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
75	0	0	0	0	1	1	4	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
76	1	0	0	0	2	2	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0
77	0	0	0	0	0	0	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
78	0	0	1	0	2	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0
79	0	0	0	0	0	0	4	2	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	4	0	0	1	0	0	0	2	4
80	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	1	0	0	0	0	0
81	0	0	0	0	0	0	2	1	1	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0
82	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
83	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
84	2	0	0	0	0	0	4	1	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
85	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	2	0	0	0	0	0	0	0	0
86	0	0	0	0	0	0	5	1	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0
87	0	0	0	0	0	0	0	2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0
88	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
89	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	1	0	0	0	0	0
90	0	0	0	0	2	1	0	2	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	4	0	0	2	0	0	0	0	0
91	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	2	0	0	0	0	0	0	0
92	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	2	2	0	0	0	0	0	0	0	0
93	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	2	0	0	0	0	2	0	0
94	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
95	0	0	0	0	2	3	0	4	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	2	2	0	0	0	0	0	2	0
96	0	0	0	0	2	0	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
97	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0
98	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0
99	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	2	0	0	0	0	0	0	2	0
100	0	0	0	0	1	1	4	2	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	2	2	0	0	0	0	1	1	0
101	0	0	0	0	0	3	2	2	2	0	0	1	0	2	6	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	1	0
102	0	0	0	0	0	0	0	2	0	0	0	0	3	1	4	0	0	0	0	2	0	0	0	0	3	2	0	0	0	0	0	1	0
103	0	0	0	0	1	1	3	0	0	0	1	1	0	0	3	0	1	0	0	1	0	0	0	0	4	0	0	0	0	0	0	1	0
104	0	2	0	0	0	0	4	2	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	3	2	2	0	0	0	0	0	0	0
105	1	0	0	0	1	0	2	1	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	2	0	0	0	0	0	1	0	0
106	1	0	0	0	0	0	0	2	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0	0	1	1	0	0	0	0	0	0	0
107	0	0	0	0	0	1	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	1	0	0
108	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
109	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	2	0	0	0	0	0	0	2	0	0
110	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0

Table A1.1 continued

APPENDIX 2

SOIL ANALYSES

Crust and soil samples were taken from some of the training areas in 1997 and 1998. 'Crust' was sampled as a consolidated layer that rests on the surface of the soil in many parts of the field area and which can be easily be removed from the surface using a knife. 'Soil' was sampled at a depth of approximately 15cm. A complete set of soil and crust samples was not achieved in either 1997 or 1998 due to some training areas having a cover of calcrete, where plants grew only from cracks in the surface, and, in other training areas, wet weather making the collection of coherent crust samples impossible. Out of 65 training areas, 48 soil samples and 42 crust samples were taken. Some training areas had only crust or soil taken and 55 of the 65 training areas had some form of soil sampling.

The original aim of the sampling was to perform various analyses on the samples to investigate the relationship of soil variables to the distribution of vegetation. However, due to time constraints it was not possible to undertake the battery of tests originally planned. The tests carried out on the soil and crust samples were conductivity, and potassium, calcium, sodium and magnesium ion extraction using water extraction. The soils were prepared by grinding then sieving through a <2mm sieve. Digestion with H_20_2 was not carried out due to uncertainty about what would happen to the calcium carbonate fraction in the soil samples during this process.

Electrical conductivity

A soil's potential to conduct electricity depends upon the concentration and charge of the ions present (Rowell, 1994). Conductivity is measured by passing a current between two electrodes in a solution. Soil was sieved to <2mm and 10g was put into 50ml of double distilled water. This was shaken on a flatbed shaker for 30 minutes and then centrifuged at 6000rpm for 20 minutes. The sample was filtered to remove sediment and then tested using a Wheatstone conductivity meter. Conductivity was measured in μmmohs (micromhos; 1 micromho being equivalent to 1 microsiemen) and the higher the value, the higher the conductivity of the extractant and therefore the soil. The results are given in Table A2.1. A high conductivity reading indicates high quantities of dissolved ions, usually calcium, magnesium, potassium and sodium ions (Hesse, 1971).

TA number	soil µmmohs	crust µmmohs	TA number	soil µmmohs	crust µmmohs
1			**34**		
2	80	75	**35**	128	115
3	112		**36**	116	
4	97	130	**37**		
5	112	150	**38**	105	139
6	640	146	**39**		
7	102		**40**		
8	205	340	**41**	95	
9	320	175	**42**		102
10	97	330	**43**	100	125
11	122		**44**	93	102
12			**45**	100	134
13	114		**46**	99	150
14	195		**47**		
15	72		**48**	65	93
16	101		**49**	71	93
17	138	128	**50**		105
18	123		**51**	77.5	129
19	86		**52**		128
20	230	203	**53**	116	121
21	660	185	**54**	76	93
22	300	106	**55**	88	118
23	101	220	**56**	85	100
24	160	138	**57**		148
25	70		**58**		
26	89		**59**		144
27	145	185	**60**	104	205
28	114		**61**		130
29	116	162	**62**		
30	99	90	**63**		139
31	138	120	**64**	260	96
32	95	150	**65**		130
33	89	125			

Table A2.1 Conductivity results for soil and crust samples

Water extraction of exchangeable ions: K^+ Na^+ Ca^{2+} Mg^{2+}

The same preparation method was used for ion extraction as for conductivity preparation. A 5:1 ratio of water:soil was used, the samples were shaken, centrifuged and filtered to produce an extractant. The extractant was then analysed using a flame photometer to measure K^+ and Na^+, and an Atomic Absorption spectrometer was used to determine Ca^{2+} and Mg^{2+} concentrations. Lanthanum chloride was used to release the Ca^{2+}. The results for soil and crust samples are shown in Tables A2.2 and A2.3 respectively.

Concentrations of K^+, Na^+, Ca^{2+} and Mg^{2+} were determined as these are likely to be the most important ions in soil processes in arid environments as soils in these areas tend to be base rich due to limited leaching under low rainfall conditions (Brady, 1984). High levels of sodium ions can indicate dispersive characteristics of soil (Black, 1957) and is a characteristic of piping soils (Heede, 1971; Alexander *et al*, 1999; Faulkner *et al*, 2000). Sodium rich soils can also account for plant nutrition problems in semi-arid areas (Black 1957).

TA number	K^+ mg/l	Na^+ mg/l	Ca^{2+} mg/l	Mg^{2+} mg/l	TA number	K^+ mg/l	Na^+ mg/l	Ca^{2+} mg/l	Mg^{2+} mg/l
1					33	17.5	25	12.82	1.24
2	4.5	10	34.3	2.1	34				
3	15.5	10	37.2	0.98	35	28.5	15	31.3	1.44
4	7	15	28.7	1.06	36	26	30	18.6	1.48
5	20	10	29.8	0.74	37				
6	13.5	715	22.2	4.54	38	11	50	18.1	1.86
7	13.5	10	33.2	0.82	39				
8	49.5	145	20.4	3.96	40				
9	21.5	95	139	3.62	41	17	15	24.42	2.48
10	27.5	20	27.5	2.56	42				
11	15	80	21.3	3.44	43	10	10	37.56	2.58
12					44	2.5	10	30.34	0.84
13	13.5	15	48.6	0.9	45	6.5	20	36.36	2.58
14	186	20	41.3	2.3	46	10	15	22.38	1.64
15	15	10	22.9	1.8	47				
16	18	15	42.1	2.82	48	3.5	10	23.98	2
17	32	25	53.7	1.48	49	14.5	15	28.56	1.4
18	17.5	15	99.2	5.84	50				
19	7	10	32.2	2.3	51	23.5	10	19.2	2.22
20	12	325	8.22	3.22	52				
21	28	730	87	9.66	53	13.5	15	25.18	0.64
22	31.5	10	194	5.5	54	2	15	24.94	0.82
23	33.5	10	16.5	1.14	55	14.5	20	17.74	2.02
24	13	195	6.16	3.32	56	10.5	10	26.86	5.64
25	16.5	5	15.7	0.42	57				
26	4	15	24.9	0.52	58				
27	7.5	105	17.3	2.58	59				
28	12.5	35	26.8	0.94	60	24.5	10	30.7	1.74
29	11.5	70	16.4	2.22	61				
30	18	35	21.2	1.92	62				
31	8	105	18.6	2.44	63				
32	14.5	50	15.4	1.46	64	5.5	105	112.2	9
					65				

Table A2.2 Results of analyses of water extracted ions for soil samples

TA number	K^+ mg/l	Na^+ mg/l	Ca^{2+} mg/l	Mg^{2+} mg/l
1				
2	8.5	15	21.44	0.72
3				
4	26	20	26.32	0.94
5	22.5	10	45.94	2.76
6	11.5	90	14.98	1.66
7				
8	50	20	366.6	2.2
9	15	10	37.08	2.76
10	58	20	208.2	3
11				
12				
13				
14				
15				
16				
17	26	15	49	0.78
18				
19				
20	27	15	57.02	1.92
21	21	45	36.3	1.34
22	33	40	23.3	1.76
23	16	10	37.34	2.06
24		45	28.68	1.94
25				
26				
27	12.5	25	38	2.26
28				
29	12.5	115	21.72	9.28
30	20	25	30.6	6.66
31	11	15	22.2	1.32
32	17.5	15	31.9	1.76
33	16.5	105	7.82	1.88
34				
35	26.5	15	26.1	0.66
36				
37				
38	11.5	85	14.66	2.6
39				
40				
41				
42	22	10	26.6	1.48
43	29.5	10	45.42	2
44	16.5	10	37.58	0.82
45	31.5	30	42.76	1.48
46	31	15	39.72	1.7
47				
48	10	25	26.02	1.12
49	22.5	10	23.96	0.98
50	9.5	10	30.4	1.42
51	39.5	10	86.8	3.7
52	20	15	44.88	0.9
53	36	10	44.98	1.36
54	10	10	37.54	0.86
55	12	10	37.26	3
56	23.5	10	30	1.74
57	26	15	90.2	1.82
58				
59	34.5	30	87.2	4.62
60	43.5	15	141.8	2.64
61	17	15	38.96	1.1
62				
63	24.5	15	45.72	1.08
64	16	10	36.34	1.7
65	24.5	10	116.2	1.9

Table A2.3 Results of analyses of water extracted ions for crust samples

The Exchangeable Sodium Percentage (ESP) and the Sodium Adsorption Ratio (SAR) were calculated for each sample (Heede, 1971 Faulkner *et al* 2000). These results are shown in Table A2.4

$$ESP = \frac{100*\text{exchangeable Na}}{(Ca+Mg+K+Na)}$$

$$SAR= [\ Na^{+}]/([Ca^{2+} \text{ and } Mg^{2+}]/2)^{0.5}$$

Cations as $mmol_{c}l^{-1}$

TA number	Soil SAR	Crust SAR	Soil ESP	Crust ESP
1				
2	0.66	1.28	29.93	46.33
3	0.65		24.79	
4	1.11	1.54	41.91	39.69
5	0.73	0.57	25.86	19.68
6	53.30	8.69	96.73	84.57
7	0.69		27.16	
8	11.35	0.42	76.92	7.92
9	3.21	0.63	50.80	24.03
10	1.44	0.56	37.46	11.71
11	6.26		77.27	
12				
13	0.86		29.78	
14	1.21		13.11	
15	0.80		30.37	
16	0.89		29.32	
17	1.36	0.86	33.60	25.99
18	0.58		17.64	
19	0.68		29.53	
20	35.85	0.79	95.75	23.53
21	29.23	2.95	90.92	57.43
22	0.29	3.18	7.14	54.40
23	0.95	0.64	25.31	23.99
24	23.18	3.24	93.32	71.94
25	0.50		21.19	
26	1.20		47.64	
27	9.19	1.57	86.63	45.28
28	2.67		60.49	
29	6.34	7.67	79.80	80.59
30	2.88	1.57	59.47	42.01
31	8.97	1.23	86.00	43.12
32	4.81	1.03	73.29	33.87
33	2.63	12.90	57.71	87.08
34				
35	1.05	1.17	29.98	33.11
36	2.66		52.97	
37				
38	4.41	7.93	73.50	83.25
39				
40				
41	1.14		36.99	
42		0.75		25.82
43	0.63	0.58	25.76	18.56
44	0.72	0.65	34.60	24.41
45	1.28	1.81	43.36	41.03
46	1.22	0.93	43.35	26.62
47				
48	0.78	1.92	36.97	54.20
49	1.10	0.80	37.14	26.95
50		0.71		29.83
51	0.85	0.42	27.62	11.90
52		0.90		28.80
53	1.19	0.59	40.27	17.60
54	1.19	0.65	48.98	26.86
55	1.77	0.63	50.00	24.88
56	0.68	0.71	27.76	23.98
57		0.63		18.44
58				
59		1.25		29.36
60	0.70	0.50	23.44	12.44
61		0.95		31.73
62				
63		0.88		27.11
64	3.79	0.65	58.94	24.50
65		0.37		11.13

Table A2.4 SAR and ESP values for soil and crust samples.

ESP is a measure of the degree of saturation of the soil exchange complex with sodium, i.e. the amount of sodium that is available in the soil. The SAR indicates how much the effects of Na^+ can be offset by the levels of availability of Mg^{2+} and Ca^{2+}. By plotting SAR and soil conductivity values together, an indication of the flocculated state of the soil can be obtained (Rengasamay *et al*, 1994; Alexander *et al*, 1999; Faulkner *et al*, 2000). Figure A2.1 shows the distribution of points for the soil and crust datasets. The regression lines indicate that in the soil dataset, there is a strong positive relationship between electrical conductivity and SAR values, and some high SAR values compared to the crust samples. This supports work done in the Mocatán catchment by Alexander *et al* (1999) and Faulkner *et al* (2000) which indicates that autostabilisation of surface material has taken place due to removal of sodium and that subsurface soils have a higher potential for dispersal

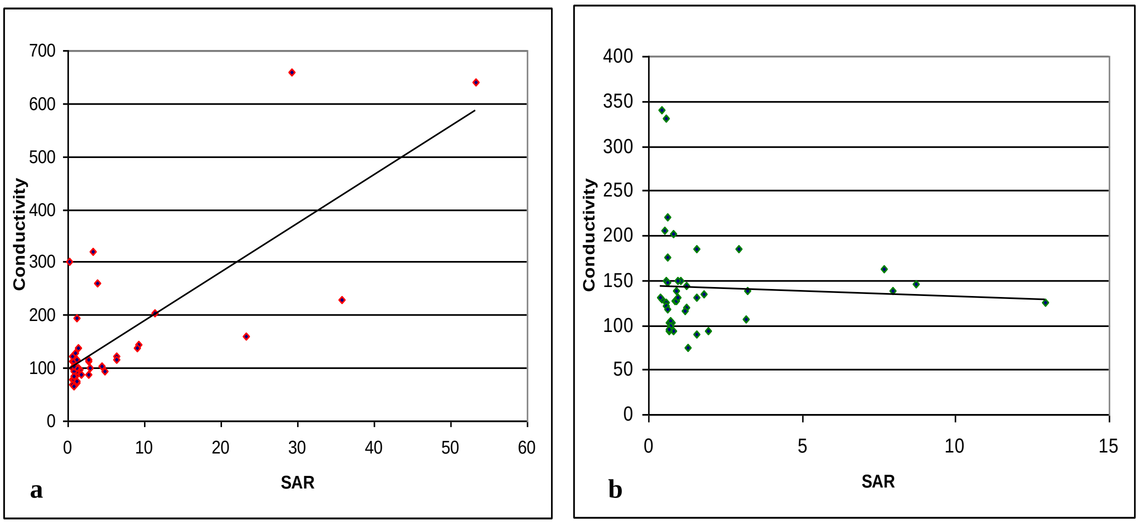


Figure A2.1 Relationship between electrical conductivity (micromhos) and SAR for a) soil samples and b) crust samples

To see if there was a difference in the relationship of SAR and electrical conductivity between samples taken from TRU and MRU sites, these were plotted separately in Figure A2.2 (no Sorbas member sites were plotted as only three samples of crust and one sample of soil were taken on this unit).

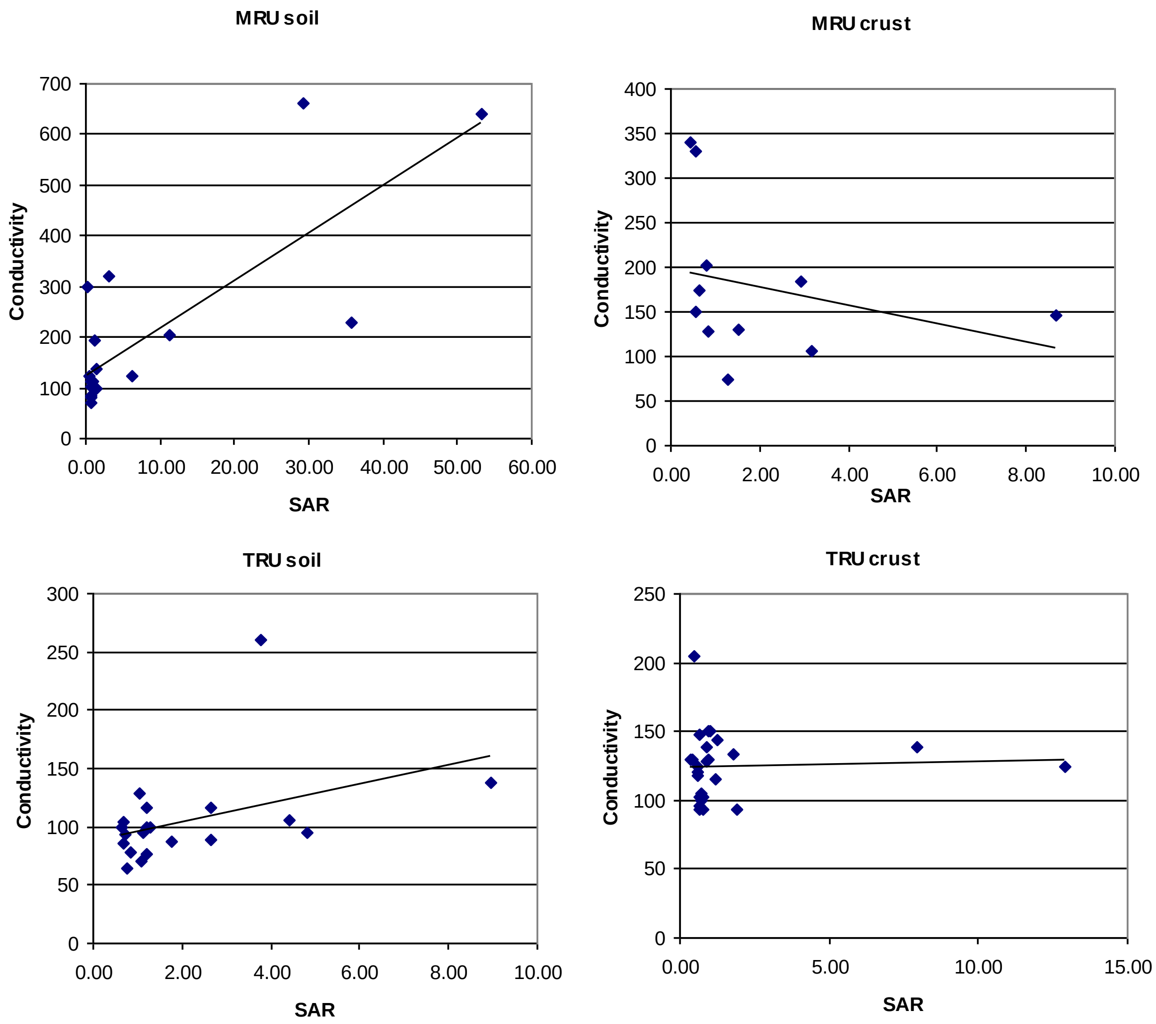


Figure A2.2 Relationship between electrical conductivity (micromhos) and SAR for soil and crust samples from TRU and MRU sites

Soil samples taken from the MRU sites have the highest dispersivity compared to the TRU and both sets of crust samples. Soil samples from the TRU sites have a lower dispersivity but still have a positive relationship between conductivity and SAR. The crust samples from both unit show lower dispersivity and those from the MRU, a negative relationship between conductivity and SAR.

APPENDIX 3

UPPER AND LOWER LIMITS OF THE NDVI CLASSES OF THE SIX CLASS NDVI IMAGE

	Min	Max	Mean	SD
Class 1	-0.166	-0.073	-0.099	0.017
Class 2	-0.073	-0.027	-0.049	0.013
Class 3	-0.027	0.013	-0.007	0.012
Class 4	0.013	0.06	0.036	0.013
Class 5	0.06	0.133	0.09	0.02
Class 6	0.133	0.627	0.191	0.069

Table A3.1 NDVI class limits for the six class NDVI image

APPENDIX 4

PERCENTAGE OF NDVI CLASS IN TRAINING AREAS

This appendix contains the tables created by the analysis of the four NDVI images when overlaid with the outlines of the 65 training areas from the 1997 and 1998 fieldwork as described in Chapter 5.

Table A4.1 NDVI 2 classes distribution within training areas

TA number	Percentage of training area in class 1	Percentage of training area in class 2
1	24	76
2	100	0
3	6	94
4	0	100
5	100	0
6	94	6
7	53	47
8	63	37
9	100	0
10	89	11
11	100	0
12	0	100
13	68	32
14	52	48
15	65	35
16	96	4
17	81	19
18	42	58
19	94	6
20	100	0
21	100	0
22	100	0
23	60	40
24	94	6
25	68	32
26	88	12
27	88	12
28	0	100
29	84	16
30	30	70
31	88	12
32	87	13
33	100	0
34	11	89
35	49	51
36	60	40
37	77	23
38	100	0
39	0	100
40	16	84
41	8	92
42	52	48
43	89	11
44	2	98
45	89	11
46	45	55
47	6	94
48	100	0
49	75	25
50	88	12
51	24	76
52	16	84
53	16	84
54	21	79
55	88	12
56	14	86
57	28	72
58	0	100
59	80	20
60	28	72
61	0	100
62	21	79
63	2	98
64	33	67
65	33	67

Table A4.2 NDVI 4 classes distribution within training areas

TA	Training area % class 1	Training area % class 2	Training area % class 3	Training area % class 4
1	8	17	45	30
2	100	0	0	0
3	0	8	92	0
4	0	0	57	43
5	3	97	0	0
6	25	69	6	0
7	0	56	38	6
8	17	46	15	22
9	100	0	0	0
10	67	22	11	0
11	68	32	0	0
12	0	0	43	57
13	19	64	17	0
14	0	52	48	0
15	39	14	39	8
16	84	13	3	0
17	0	81	19	0
18	10	34	56	0
19	86	9	0	5
20	86	14	0	0
21	85	15	0	0
22	100	0	0	0
23	12	50	21	17
24	30	63	7	0
25	22	47	31	0
26	31	53	16	0
27	36	51	13	0
28	0	0	64	36
29	34	50	16	0
30	0	29	71	0
31	78	11	11	0
32	71	16	2	11
33	75	25	0	0
34	0	12	74	14
35	0	51	33	16
36	8	51	15	26
37	22	54	24	0
38	32	68	0	0
39	0	0	66	34
40	0	17	83	0
41	0	8	80	12
42	5	48	44	3
43	0	89	11	0
44	0	2	98	0
45	3	86	11	0
46	0	44	66	0
47	0	8	92	0
48	63	37	0	0
49	3	73	25	0
50	0	89	11	0
51	0	27	0	73
52	0	21	78	1
53	0	17	83	0
54	0	22	33	45
55	60	28	12	0
56	0	15	34	51
57	0	28	72	0
58	0	0	68	32
59	20	60	20	0
60	0	27	44	39
61	0	0	88	12
62	0	21	79	0
63	0	7	78	20
64	11	22	67	0
65	0	22	67	11

Table A4.3 NDVI 6 classes distribution within training areas

TA	Class 1	Class 2	Class 3	Class 4	Class 5	Class 6
1	0	9	16	25	50	0
2	37	63	0	0	0	0
3	0	0	8	58	34	0
4	0	0	0	17	73	10
5	5	4	91	0	0	0
6	0	76	18	6	0	0
7	0	6	44	25	25	0
8	9	12	41	8	30	0
9	96	4	0	0	0	0
10	33	33	22	11	0	0
11	60	40	0	0	0	0
12	0	0	0	15	57	28
13	21	14	22	42	1	0
14	0	0	52	24	24	0
15	34	20	11	17	18	0
16	76	8	13	3	0	0
17	0	14	60	26	0	0
18	9	11	22	58	0	0
19	57	28	9	0	6	0
20	38	59	3	0	0	0
21	53	36	11	0	0	0
22	88	18	0	0	0	0
23	0	37	22	22	18	0
24	0	55	39	6	0	0
25	1	44	24	31	0	0
26	10	58	17	15	0	0
27	0	45	43	4	8	0
28	0	0	0	42	30	28
29	25	21	39	15	0	0
30	0	22	8	66	4	0
31	50	28	11	11	0	0
32	71	5	11	0	13	0
33	21	55	24	0	0	0
34	0	4	9	34	53	0
35	0	0	45	38	9	8
36	0	28	31	12	14	15
37	22	22	31	25	0	0
38	10	35	47	8	0	0
39	0	0	0	8	92	0
40	0	0	17	51	32	0
41	0	0	8	44	48	0
42	0	22	30	17	31	0
43	0	7	82	11	0	0
44	0	0	1	26	73	0
45	0	26	62	12	0	0
46	0	0	42	57	1	0
47	0	0	8	27	65	0
48	10	82	8	0	0	0
49	0	14	59	27	0	0
50	0	14	75	11	0	0
51	0	8	16	0	17	59
52	0	0	17	46	37	0
53	0	0	17	59	24	0
54	0	11	11	20	36	22
55	20	43	22	15	0	0
56	0	5	6	7	30	52
57	0	0	26	74	0	0
58	0	0	0	15	53	32
59	13	19	43	16	9	0
60	0	0	25	11	39	25
61	0	0	0	27	71	2
62	0	0	5	95	0	0
63	0	0	2	11	79	9
64	0	22	12	33	33	0
65	0	7	11	32	50	0

Table A4.4 NDVI 8 classes distribution within training areas

TA	Class 1	Class 2	Class 3	Class 4	Class 5	Class 6	Class 7	Class 8
1	0	8	2	14	7	17	52	0
2	13	87	0	0	0	0	0	0
3	0	0	0	8	52	39	1	0
4	0	0	0	0	0	24	76	0
5	5	1	25	69	0	0	0	0
6	0	37	40	17	6	0	0	0
7	0	1	20	24	10	21	24	0
8	9	8	28	19	0	14	22	0
9	95	5	0	0	0	0	0	0
10	11	56	11	11	11	0	0	0
11	59	21	20	0	0	0	0	0
12	0	0	0	0	0	21	78	1
13	21	0	31	11	28	9	0	0
14	0	0	4	47	12	31	6	0
15	34	17	3	0	14	22	10	0
16	73	12	0	12	0	3	0	0
17	0	3	19	26	44	8	0	0
18	10	10	12	11	47	10	0	0
19	46	38	6	4	0	0	6	0
20	33	67	0	0	0	0	0	0
21	41	48	0	11	0	0	0	0
22	77	23	0	0	0	0	0	0
23	1	25	17	19	21	0	17	0
24	0	32	24	37	7	0	0	0
25	0	22	25	22	14	17	0	0
26	6	45	23	11	12	3	0	0
27	0	40	48	0	4	0	8	0
28	0	0	0	0	28	15	40	17
29	7	36	13	28	9	7	0	0
30	0	11	11	8	41	26	3	0
31	51	27	0	0	22	0	0	0
32	70	2	16	0	0	0	12	0
33	15	60	8	17	0	0	0	0
34	0	3	0	8	12	54	23	0
35	0	0	33	14	31	6	8	8
36	0	18	20	20	1	11	28	2
37	22	12	20	22	24	0	0	0
38	10	21	35	26	8	0	0	0
39	0	0	0	0	0	35	65	0
40	0	0	0	11	51	30	8	0
41	0	0	0	8	29	39	24	0
42	0	12	22	18	15	30	3	0
43	0	6	39	38	16	1	0	0
44	0	0	0	1	4	82	13	0
45	0	3	52	33	12	0	0	0
46	0	0	0	44	33	23	0	0
47	0	0	1	0	17	59	23	0
48	0	86	13	1	0	0	0	0
49	0	1	23	44	13	19	0	0
50	0	0	36	12	51	1	0	0
51	0	0	8	16	0	0	41	35
52	0	0	10	8	17	49	16	0
53	0	0	0	17	28	43	12	0
54	0	0	10	11	20	3	45	11
55	0	63	0	22	15	0	0	0
56	0	0	15	2	9	12	20	42
57	0	0	0	15	74	11	0	0
58	0	0	0	0	16	20	44	20
59	8	13	17	38	15	0	9	0
60	0	0	4	22	5	14	44	11
61	0	0	0	0	6	39	55	0
62	0	0	0	0	75	25	0	0
63	0	0	0	2	0	33	65	0
64	0	10	12	2	32	33	11	0
65	0	0	12	8	13	56	11	0

APPENDIX 5

BOXPLOTS SHOWING SOIL CHEMISTRY AND NDVI CLASS

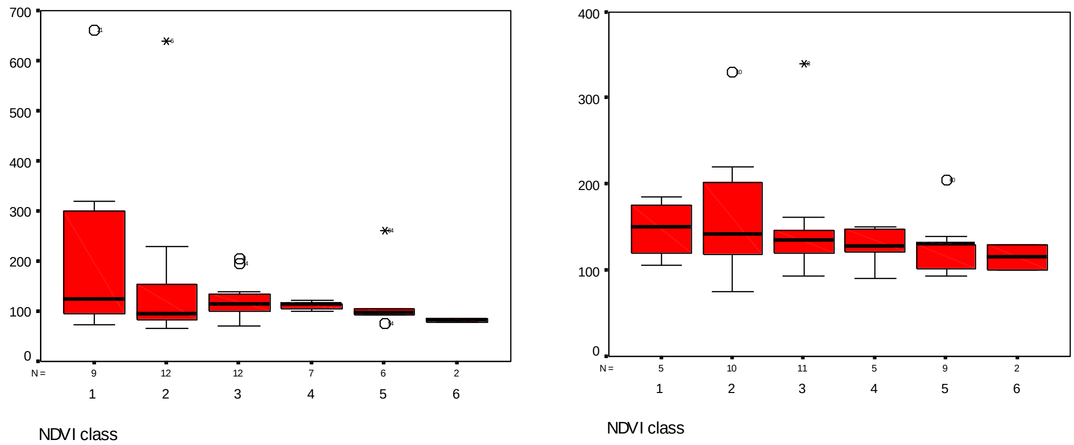


Figure A5.1 Boxplot of soil and crust conductivity (µmmhos) and NDVI class

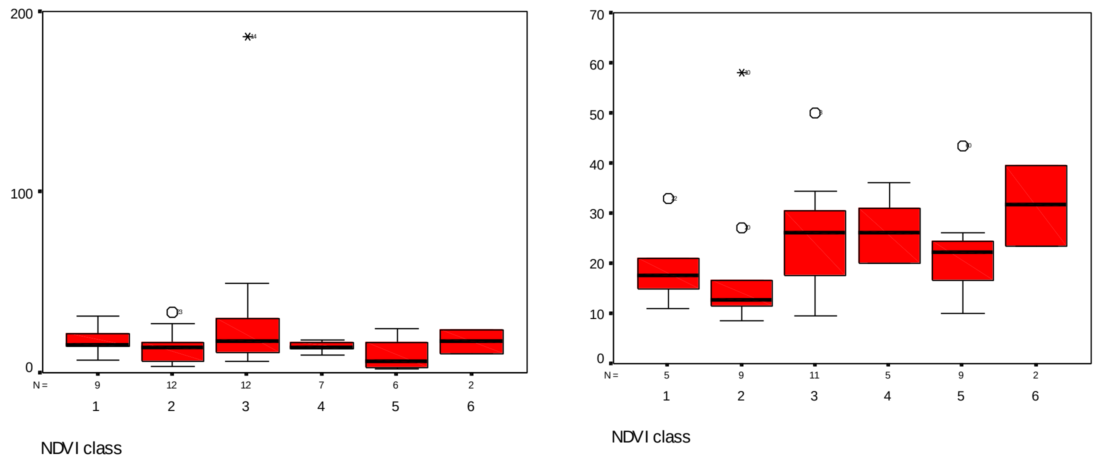


Figure A5.2 Boxplot of soil and crust potassium (mg/l) and NDVI class

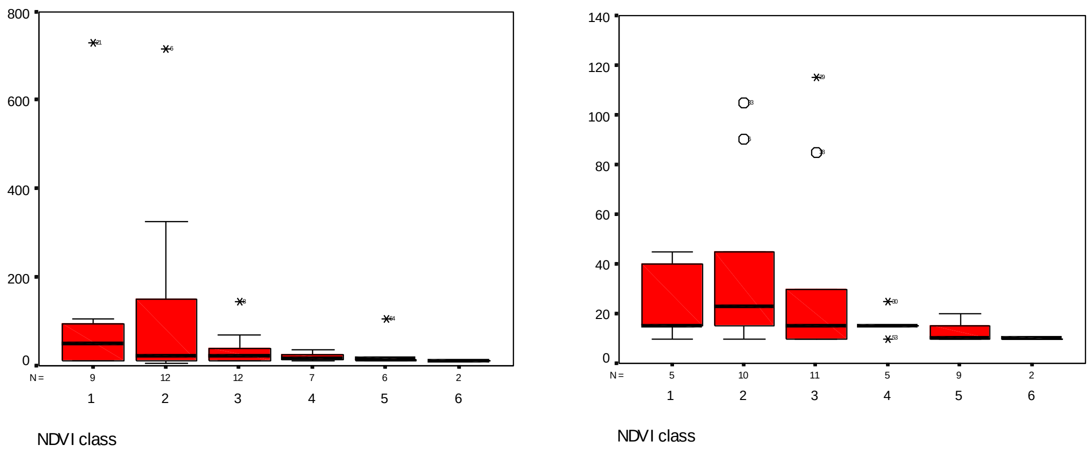


Figure A5.3 Boxplot of soil and crust sodium (mg/l) and NDVI class

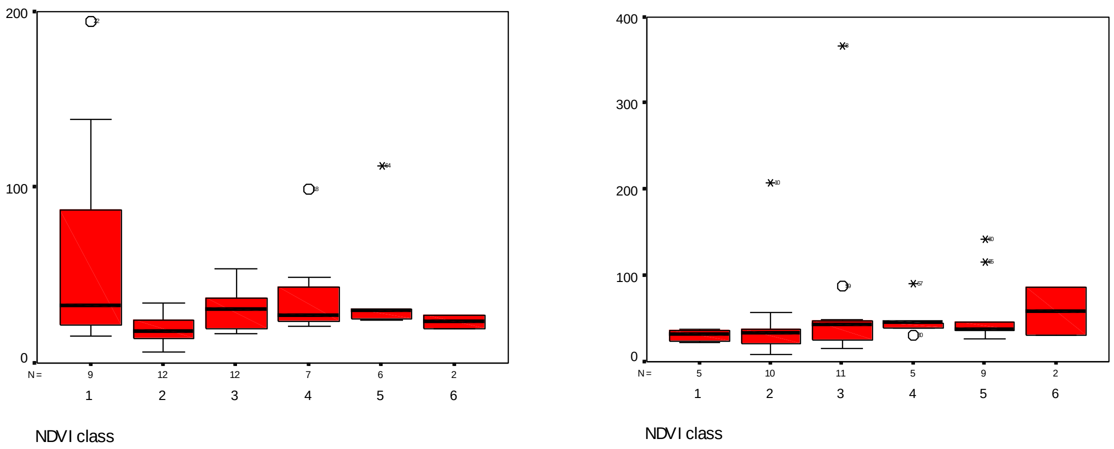


Figure A5.4 Boxplot of soil and crust calcium (mg/l) and NDVI class

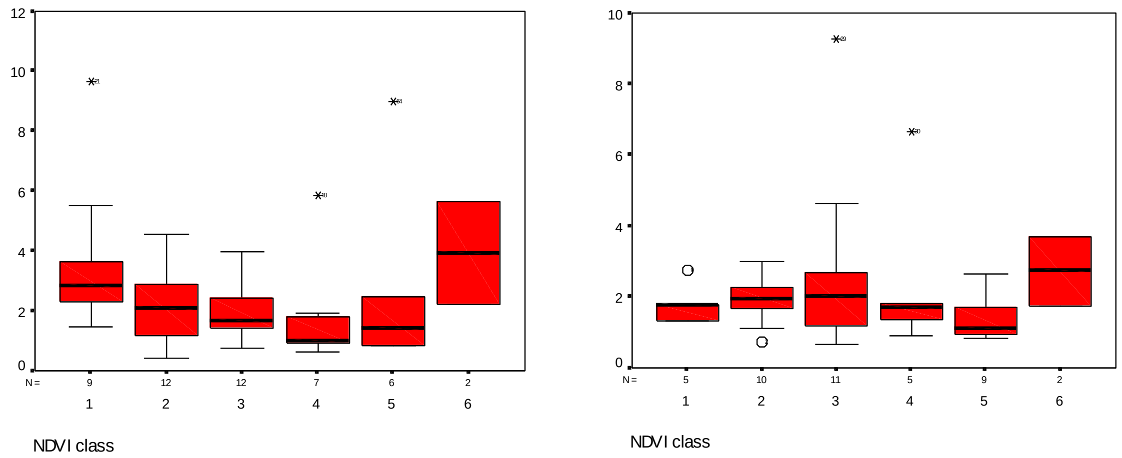


Figure A5.5 Boxplot of soil and crust magnesium (mg/l) and NDVI class

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